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PROSPECTS FOR ELECTRIC VEHICLES A STUDY OF LOW-POLLUTION-POTENTIAL VEHICLES — ELECTRIC

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The major purpose was to assess the state of the art in the technologies on which the future development of electric highway vehicles depends. The assessment is made on the basis that there will be no major change in the patterns of urban transportation and focuses upon the technical requirements of the vehicle. As a framework for the study, technical and, to a lesser extent, cost criteria were established for six classes of electric vehicles, most of which correspond closely in performance to existing conventionally powered types. On the basis of these criteria the prospects for vehicle application of various electric motor and control systems and a wide range of electrical power sources including batteries, fuel cells, and engine-generator-battery hybrids are compared. The most promising systems for further development are identified and the magnitude of the shortfall in their present characteristics ~~are~~ estimated. Recommendations are made for the expansion of future effort in these areas, taking into account the expected contributions from existing programs in the public and private sectors of the economy. The technology of electric vehicles appears to be attainable, quite possibly at an acceptable cost. A very substantial technical effort is called for if the required technologies are to be brought to maturity. The technical risks of this endeavor are too great for the investment to be borne by private capital alone, particularly since the major objective is a technology desirable for its social good rather than for its profit potential.

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U. S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
Public Health Service
Consumer Protection and Environmental Health Service
National Air Pollution Control Administration
Raleigh, North Carolina
October 1969

FOREWORD

The information contained in this report was submitted to the National Air Pollution Control Administration as a result of a study performed under contract. It is apparent that the information contained herein is of value to others interested in air pollution control. To supply their need, this report is being reprinted in essentially the same form in which it was submitted to the National Air Pollution Control Administration by the contractor.

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I. SUMMARY

A. PURPOSE AND SCOPE

This report presents the results of a study conducted by Arthur D. Little, Inc. for the National Center for Air Pollution Control concerning electrically powered vehicles of low pollution potential. A parallel study concerning unconventional thermal, mechanical, and nuclear power sources for vehicles has recently been completed by the Battelle Memorial Institute – Columbus Laboratories.*

The major purpose of the Was ~~present study~~ is to assess the state of the art in the technologies on which the future development of electric highway vehicles depends. The assessment is made on the basis that there will be no major change in the patterns of urban transportation and focuses upon the technical requirements of the vehicle. As a framework for the study, technical and, to a lesser extent, cost criteria were established for six classes of electric vehicles, most of which correspond closely in performance to existing conventionally powered types. On the basis of these criteria the prospects for vehicle application of various electric motor and control systems and a wide range of electrical power sources including batteries, fuel cells, and engine-generator-battery hybrids are compared. ~~The study identifies~~ the most promising systems for further development are identified and ~~estimates~~ the magnitude of the shortfall in their present characteristics are estimated. Recommendations are made for the expansion of future effort in these areas, taking into account the expected contributions from existing programs in the public and private sectors of the economy.

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B. FINDINGS

(1) The technical state of the art in motors and controls is generally more advanced than that of power sources in relation to the needs of electric highway vehicles.

(2) Minimum energy and power densities for electrochemical power sources capable of giving acceptable performance in the six classes of vehicles are listed below. The figures are based on reasonable estimates of the weight assignable to the power source and propulsion system and of the weight of suitable electric motors and controls.

	Family Car	Commuter Car	Utility Car	Delivery Van	City Taxi	City Bus
Conventional construction						
Energy density (w-hr/lb)	135	41	26	50	96	81
Power density (w/lb)	94	46	40	55	45	36
Lightweight construction						
Energy density (w-hr/lb)	87	28	18	33	64	55
Power density (w/lb)	60	31	28	36	30	25

---

* Battelle Memorial Institute, "Study of Unconventional Thermal, Mechanical, and Nuclear Low-Pollution-Potential Power Sources for Urban Vehicles," by J. A. Hoess, *et al.*, Summary Report to U.S. Dept. of Health, Education and Welfare, March 15, 1968.

(3) In a hybrid power source the important technical parameter for the battery is the power density; energy density is of only secondary importance. The power densities required for batteries in vehicles of conventional construction having 40% of the peak power supplied by a gas piston engine and 60% by a battery are as follows:

	Family Car	Commuter Car	Utility Car	Delivery Van	City Taxi	City Bus
Power density (w/lb)	92	38	34	43	35	25

For the family car, the power density requirement is virtually equal to that for a purely battery powered vehicle; for the other vehicles the requirement is not much lower.

(4) The technical requirements for the family car power source can be met only by high temperature alkali-metal batteries; these systems, as yet in the early stages of development, are also the most promising for the commuter car, the delivery van, and the city taxi. If lightweight construction is used metal-air batteries are potentially capable of meeting the requirements for all vehicles except the family car. Alkali-metal batteries with organic electrolytes seem likely to have insufficient power density for use in vehicles, and combining them with high-power-density batteries is clearly too costly a solution.

(5) Although of limited energy density the lead-acid battery seems likely to be capable of meeting the requirements of the utility car of lightweight construction.

(6) The fuel cell's prospects as an electric vehicle power source seem unfavorable, mainly because of its extra complexity and cost and its lower power density. Its much simpler mode of refueling, however, would be a major advantage.

(7) The most practical present choice of motor for an electrical vehicle is a high-speed dc machine with mechanical commutator, operating at speeds of up to 19,000 rpm for the smaller vehicles, air cooled, and with integral speed reducers. Such motors are already being developed for aerospace and military applications.

Control of high-speed dc motors is best achieved by a chopper circuit containing silicon controlled rectifiers (SCR's). These circuits are at present rather heavy for the amount of power they control. However, they can be developed for operation at high voltage (500 volts in the case of the bus and family car) so as to be relatively lightweight.

(8) Because ac motors can be run at higher maximum speeds, they have a higher output per pound than dc motors and hence permit weight reduction; these will doubtless be adopted when the technologies for inversion and control are further advanced. The development of solid-rotor ac motors instead of the squirrel-cage induction type will lead to greater weight reduction and simplify the problems of inversion and control.

The controller for the ac motor would be a variable-frequency, variable-voltage SCR inverter circuit. Experimental circuits developed to date are, however, extremely heavy and require capacitor banks across the battery when an induction motor is used.

(9) Regenerative braking would reduce the power source requirements somewhat for vehicles that make frequent stops. However, for the majority of vehicles, the amounts of energy recovered do not appear likely to justify the added cost and complexity.

(10) The recharging of electric vehicles is best achieved at slow rates. Rapid recharge would call for large investment in facilities and would introduce a number of severe technical difficulties. Occasional long trips could be accomplished by replacement of batteries at service stations.

(11) The first costs of electric vehicles will inevitably be higher than those of equivalent internal-combustion-powered vehicles. Part of this may be offset by lower maintenance requirements and longer life, but much of the difference would have to be regarded as a social cost for the elimination of air pollution. If an additional $1,000 is acceptable in the retail cost of the family car, the cost target for the battery is in the vicinity of 95 cents per pound. Allowable costs in the commercial vehicles would be somewhat higher. High-temperature alkali metal batteries have some prospects of meeting these cost requirements. Metal-air batteries are likely to be somewhat costlier but might still be acceptable for commercial vehicles.

(12) The duplication in functional capabilities tends to give hybrid vehicles a fundamentally higher cost structure than pure electrics. The higher cost may, however, be acceptable in commercial vehicles, and existing technology would permit low cost lead-acid batteries to meet the power density requirements of a hybrid city bus, making this vehicle an attractive possibility.

(13) Present federal spending on research and development on electrochemical power sources, and exclusive of the major fuel cell hardware programs for space vehicles, is estimated to be in the vicinity of $10 million annually. However, only a small proportion of this is directly relevant to the needs of electric vehicle development for civilian use. Expenditure by private industry on power source development relating to electric vehicles is estimated at $5-7 million annually.

(14) The time scale for the development of electric vehicles will be determined mainly by progress in battery technology and by the magnitude of the effort which sustains it. Assuming that the latter is adequate, high-temperature alkali metal batteries appear likely to require a period of the order of ten years before they can be considered as practical and economic power sources for use in vehicles. Certain metal-air systems, having promise for application in commercial vehicles, might be made available in a somewhat shorter period. At least comparable periods of time would be needed to develop sufficiently low cost manufacturing processes for the motors and controls.

C. RECOMMENDATIONS

(1) The power source requirement for electric vehicles calls for a major and sustained effort in the development of batteries with high energy density and high power density. The requirements for the most significant classes of vehicles can be fully met only by batteries having alkali-metal anodes and molten salt (or possibly ceramic) electrolytes, which necessitate high temperature operation. If such batteries are to be brought to maturity within a ten-year period a coordinated program under federal sponsorship should be set up to do the following:

(a) Explore comprehensively the electrochemistry of the limited number of elements having the reactivity and potential low cost availability to function as anode or cathode materials in high-temperature alkali metal batteries. The physical chemistry of molten salt and ceramic systems appropriate for use as electrolytes should also be investigated.

(b) Examine the materials selection problems associated with such batteries, giving particular regard to choice of current collectors, separators, sealants, and structural materials generally.

(c) Investigate suitable low-cost engineering solutions for the problems of thermal insulation, temperature control, and safety, which are common to all members of this class of batteries.

(d) Develop, in collaboration with industry, the one or two most practical battery systems arising from these research programs.

(2) Support should be given to the further development of rechargeable metal-air batteries. For those of relatively conventional design the principal problems rest with the basic electrochemistry. Other types, which employ engineering solutions to the fundamental electrochemical difficulties, should be supported in the development stage.

(3) The development of high rate lead-acid batteries should be supported in view of their prospects in hybrid-powered commercial vehicles.

(4) The problems of adapting the technologies of high speed air-cooled dc commutator electric motors and of sophisticated dc chopper controllers for low cost mass production should be investigated. Studies should be initiated as to the techniques – such as extensive automation and use of microelectronic modules – by which cost reductions might best be achieved.

(5) Possible techniques for the low cost manufacture of solid-rotor synchronous ac motors and of squirrel-cage ac induction motors with inverters should be investigated. The technology of these machines (known also as brushless dc motors) would also benefit directly from the advances in dc chopper controllers and high-speed dc motors.

(6) Some general encouragement should be given to developing the use of lightweight materials, particularly plastics, reinforced and otherwise, and the lighter metals, for use in present day conventional automobiles. Advances in this area will help to hasten the advent of electrically powered vehicles by lessening the severity of the requirements on the power source. Similar considerations hold for tires designed to minimize rolling resistance.

(7) The potential merit of electric vehicles, relative to other approaches toward alleviation of the air pollution problem, should be periodically re-evaluated in the light of the progress and pattern of development taking place in the various contributing technologies.

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II. APPROACH

The pollution of the atmosphere by the exhaust products of the internal combustion engine, particularly in the cities, is a subject of increasingly serious concern. Viewed as a purely technical problem, abatement can be approached in several ways. The most straightforward is to modify the engine and exhaust system with devices which will either suppress pollutants or convert them into less noxious products. A great deal of effort is presently being expended in this approach, and it may well prove to be the most satisfactory for the immediate future. However, the tendency of an internal combustion engine to pollute increases with its age, and the effectiveness of conversion devices, usually involving catalytic combustion, decreases with time; thus the suppression of pollution may be adequate in a new vehicle but quite unsatisfactory by the time it is two or three years old.

Another approach is to replace the internal combustion engine with a type of prime mover that has no significant pollution problem. In principle there are a large number of possibilities, including electric power sources, external combustion systems, inertial energy systems and a variety of exotic energy conversion devices. In practice, however, the practical options are quite limited.

A third approach is to alter the transportation system through major changes in conventional public facilities or through such concepts as the rental of small, self-driven, taxi-like vehicles for journeys within the urban centers.

The subject matter of this study is concerned with the second general approach and specifically with the prospects for self-propelled electric vehicles.

It is necessary to make numerous assumptions as the basis for a study of this type, many of them rather arbitrary, and many of them having a significant bearing on the findings of the study. We are well aware of this and consider our work as a first approximation which may suggest directions for further more refined and specific analysis.

The study is based upon a consideration of the requirements for six types of electric vehicles: a family car, a commuter car, a utility car, a delivery van, a city taxi and a city bus. With the exception of the utility car these represent the great majority of vehicles that now provide transportation in the urban environment. The model for the family car is the familiar full-sized, six-passenger automobile, which represents almost 80% of the total vehicle population of this country. The commuter car is modeled on the much smaller, four-seater, European-type compact car, whose population has been steadily increasing in recent years, primarily for commuter travel. The delivery van is somewhat less well defined but can be regarded as a typical panel truck with a carrying capacity of about one ton. The city bus is the characteristic full-sized vehicle with a carrying capacity of about 80 passengers including standees. The other two vehicles contain an element of invention. The city taxi is outwardly similar to the family car but has been arbitrarily assigned lower performance capabilities in view of its working pattern in the dense traffic of city streets. The utility car is a small vehicle intended purely for local trips, such as might be taken by a

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housewife on shopping errands or possibly for short-range commuting. While each of these vehicles is a candidate for electric propulsion in its own right, it is clear that the greatest interest attaches to the family car in view of its preponderance in the total vehicle population.

The first step in the selection of weight and performance parameters for the various vehicles involved an examination of the published data for virtually all vehicle models manufactured over the last ten years in the United States and Western Europe. From these vehicle specifications, reasonably appropriate values were established for weight and performance in each of the classes. The calculation of power requirements necessitated some assumptions about frontal cross-sectional area, degree of streamlining, and tire friction. The values chosen for the drag coefficient were liberally low, reflecting the best present aerodynamic design practice, while the estimates for tire friction were conservative, since there is some element of compromise with safety in the design of low-friction-loss tires.

The parameters for acceleration are believed to represent reasonable values for new vehicles. It would not be fair, however, to insist that the electric vehicle should have an acceleration equal to that of a typical new, carefully tuned vehicle with a conventional engine. The performance of an electric vehicle should remain fairly constant with time, while that of most conventional vehicles is at least fractionally lower than when new after three or four years on the road. Accordingly, adverse weighting of the vehicles that formed the basis for the assumed parameters was at least partially offset by considering only vehicles whose power capabilities were on the lower side of normal. Thus, the acceleration for the family car is typical of that for a six-cylinder vehicle, even though more than 80% of the vehicles in this category now have eight-cylinder engines.

Probably of even greater influence on the findings of the study than the assumptions about performance are those about driving cycles and their relationship to vehicle range. The energy consumed by a vehicle per mile of driving is very heavily influenced by the number of stops made, by the rate of acceleration, and by the velocity. The selection of any particular driving pattern thus has a major effect on the range obtainable from a given quantity of stored energy. Fortunately, the arbitrariness of the assumption is partially offset by the fact that vehicles are generally driven at relatively high speed when not in stop-and-go traffic; the energy consumption per mile is therefore very much more constant than it would be if people were in the habit of driving at modest speed on the open road.

The technical requirements for the six classes of vehicles have been established by the following procedure. The maximum power requirements corresponding to the maximum acceleration performance assumed for the vehicles were first calculated; this provided a basis for setting the power rating of each vehicle. The requirements for stored energy were calculated from the energy expenditure for each vehicle when following a standard urban driving cycle. (Since the driving pattern for the city bus involves an unusual number of stops per mile, a separate driving cycle was developed and used for this vehicle.) Assumptions about total range varied with the type of vehicle; in general, the criterion was to take a relatively low value but one that would be justifiable in the application for which the vehicle was intended. For example, the family car has a range of 200 miles, the commuter car 100 miles, and the utility car only 50 miles.

To bring into focus the technical requirements for electric vehicles, our approach has been to remove conceptually from the conventionally powered vehicles those components (engine, transmission, radiator, muffler, etc.) which are inseparably associated with the functioning of the internal combustion engine and to replace them with an electrical power source, motors, and a control system of equal total weight. This procedure considers electric vehicles as modifications and neglects the possibilities of weight optimization which would result from special design. Our basis has been some prior work by Hoffman,* who analyzed the weights of the components of a great many vehicle models and found a recurring pattern in the weight distribution. Among passenger cars whose size and power varied over a wide range, for example, the weight of the replaceable components was never far from 35% of the curb weight of the vehicle. Hoffman also considered the proportion of vehicle weight which could be assigned to the power source and propulsion unit if lightweight materials such as plastic body panels and magnesium frames were used. He concluded that this would raise the allowable proportion to 50%. Our analysis has been conducted on the bases of both conventional and lightweight construction, using proportions close to Hoffman's for the cars and estimated values for the delivery van and city bus.

A major element in our further analysis is the assumption of representative weights for the motors and controls used in these various vehicles so that a total weight could be allocated to the power source. The pattern of the study is thus to relate the prospects for the electric vehicle largely to the requirements of its power source. The justification for this assumption is that the technology in the electrical and electronic areas is relatively further advanced toward the vehicle objective than is that of electrochemical power sources. Projections in these areas can thus be made with relatively greater confidence. The derived results of the above calculations are then expressed as requirements for energy density (watt-hours per pound) and power density (watts per pound) for the power source.

Power source volume is also of some significance, but to a first approximation it would seem secondary to considerations of weight. The great majority of the possible power sources which are candidates for vehicle application have densities which are broadly comparable with each other and with the power systems they would replace. Moreover, the electrochemical power sources would seem to have greater flexibility for utilizing internal space within the vehicle.

The question of mechanical-electrical hybrid power sources has also been considered as part of this study, although practical power systems of this type would inevitably produce some degree of air pollution. No attempt has been made to consider the relative merits of various hybrid approaches on the basis of their relative contribution to air pollution; they have been regarded solely as alternative electrical power sources. The approach was to assign the available power source weight to the engine-generator-battery combination and from the estimated weights for the first two components determine the power densities required from the battery.

Much of this report is concerned with a review of the present and projected state of the art in the technologies of electric motors and control systems and electrochemical power sources. Using the technical requirements of the electric vehicles as a yardstick for assessment of present achievement and future progress, we have developed some conclusions and recommendations concerning the preferred direction for further effort.

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* G. A. Hoffman, *Transportation Research,* Vol. 1, No. 3, 1967.

The question of costs is of comparable importance but is even more difficult to bring into focus, since it frequently relates to manufacturing processes which in many cases are barely in the conceptual stage. Such conclusions about costs as can be drawn are, however, integrated into our assessment of the needs for further research and development programs.

The conclusions to be drawn from our study, while cautiously optimistic for the prospects of electric vehicles, are not to be interpreted as indicating the likelihood of their imminent appearance. A vast amount of further technical effort is called for if the large-scale use of electric vehicles is to become a reality, even twenty years from now. Nevertheless it seems that it can be done, and the effort should be made if the social cost of air pollution is sufficiently great and other approaches to the problem are less attractive. Such decisions, however, are in the political realm; this report is to be considered primarily as a contribution to the technical evaluation of the problem.

III. CRITERIA FOR ELECTRIC VEHICLES

A. DEVELOPMENT OF VEHICLE SPECIFICATIONS

In this section technical criteria are established for the six classes of electrical vehicles. As a basis for this, the electric vehicles have been considered as comparable alternatives to existing vehicles powered by internal combustion engines. Though new requirements for vehicles do appear from time to time, one year's car generally behaves very much like another's, and motorists have become accustomed to certain kinds of response from the vehicles they drive. This is not to say that all of today's vehicles show identical performance but, rather, that there are minimum standards of acceleration and comfort to which any new vehicle must conform if it is to achieve commercial success. Furthermore, any vehicle which cannot perform like most of those with which it mingles presents a serious hazard on crowded roads.

In addition to performance, the vehicle controls must be similar in "feel" to those of conventional vehicles. This, however, is largely a matter of proper design of the electrical controls and does not necessarily involve weight and power consumption.

The choice of vehicles and of vehicle parameters for this study (Table 1) were made after discussions with representatives of the National Center for Air Pollution Control and Battelle Memorial Institute. Most of these vehicles represent types of conventional motor vehicles now used in and around our cities. For completeness, we have included in the study a "utility" vehicle, whose performance is not comparable with that of today's highway vehicles but which may find acceptance in specialized uses and locations. Its specifications correspond closely to those of many of the electric vehicles developed in the United Kingdom.

The reported performances of a number of selected types of internal combustion powered vehicles in each of the six classes were examined and norms were established for their maximum acceleration; these figures are tabulated on lines 1 and 2. Using the actual acceleration curves as a guide we then drew standardized acceleration curves and normalized them to the acceleration specifications. These curves, shown in Figure 1, were used as the basis for all further calculations of maximum power and energy requirements.

The maximum performance of a vehicle can be concisely stated as the relationship between velocity and time while it is driven from rest at full power. It is not necessary to consider grade climbing separately, because at any given speed there is a simple relationship between maximum level-road acceleration and grade climbing ability.

The weights assigned to the vehicles listed in Table 1 were based on data for current vehicles of similar capacity and performance. The weights assignable to propulsion, energy storage, controls, etc. in line 7a were obtained by use of the general procedure of Hoffman* – i.e., by totaling the weights for all those components of the conventionally powered

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TABLE 1

ELECTRIC VEHICLE SPECIFICATIONS

Assumptions		Family Car	Commuter Car	Utility Car	Delivery Van	City Taxi	City Bus
1. Acceleration to	(mph)	60	60	30	40	40	30
2. in	(sec)	15	30	10	20	15	15
3. Range	(mi)	200	100	50	60	150	120
4. Seats or payload	(lb)	6	4	2	2,500	6	10,000
5. Loaded weight*	(lb)	4,000	2,500	1,700	7,000	4,000	30,000
6. Curb weight	(lb)	3,500	2,100	1,400	4,500	3,500	20,000
7. Weight assignable to propulsion, energy storage, controls	(lb)						
a. conventional construction		1,250	750	500	1,400	1,250	5,000
b. lightweight construction		1,750	1,050	700	2,000	1,750	7,000
8. Frontal area	(ft^2)	25	18	18	42	25	80
9. Drag coefficient		0.35	0.25	0.25	0.85	0.35	0.85
10. Elec. transmission efficiency	(%)	82	77	72	79	76	85
Derived Parameters							
11. Max. power delivered by motors	(kw)	70	22	12	49	36	135
	(hp)	94	30	16	66	48	180
12. Max. output of power source	(kw)	85	29	17	62	47	159
13. Max. velocity	(mph)	100	80	65	56	77	55
14. Delivered energy	(kwh)	100	20	8	45	75	300
15. Stored energy	(kwh)	122	26	11	57	99	353
16. Weight of motors, transmission, and controls	(lb)	348	118	82	259	210	615
17. Weight assignable to power source	(lb)						
a. conventional construction		902	632	418	1,141	1,040	4,385
b. lightweight construction		1,402	932	618	1,741	1,540	6,385
Power Source Requirements							
18. With conventional construction							
energy density	(w-hr/lb)	135	41	26	50	96	81
power density	(w/lb)	94	46	40	55	45	36
19. With lightweight construction							
energy density	(w-hr/lb)	87	28	18	33	64	55
power density	(w/lb)	60	31	28	36	30	25

*The loaded weights given for the cars and taxi are not the maximum which they are capable of carrying but rather reflect typical usage.

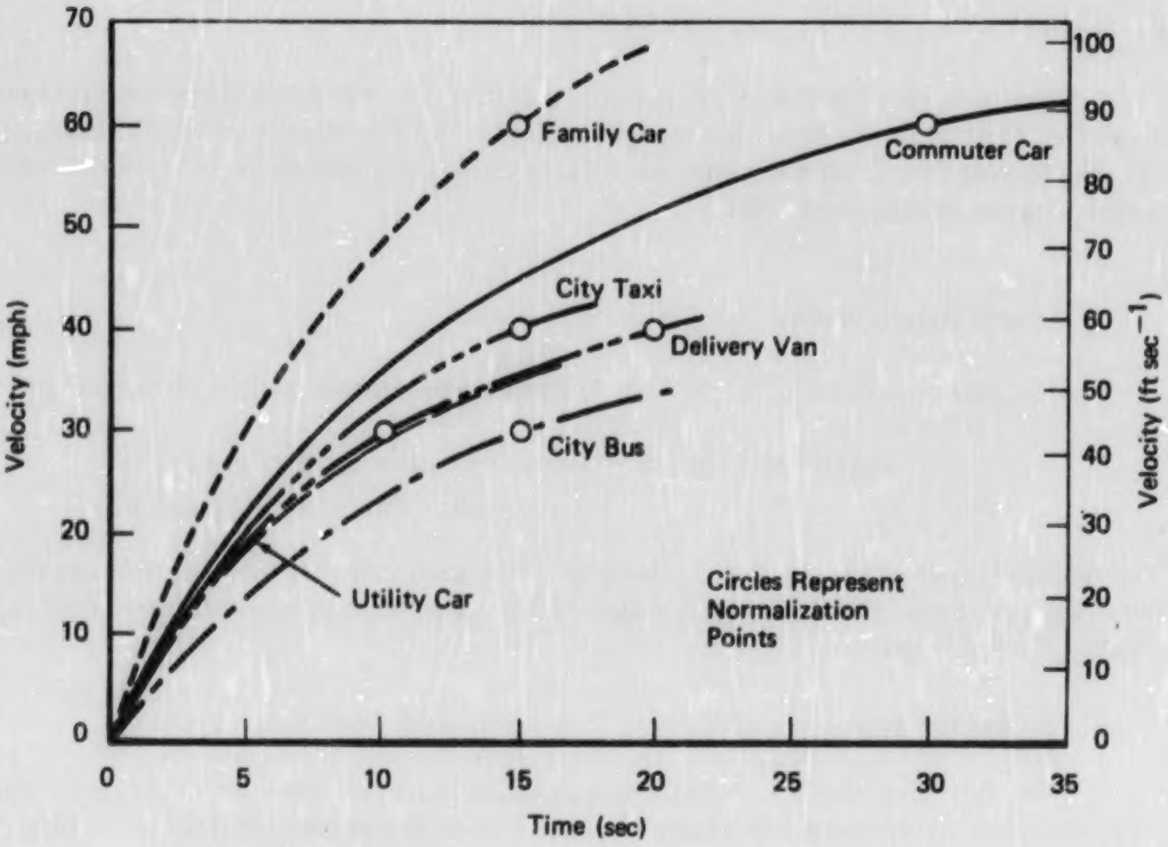

FIGURE 1 STANDARDIZED ACCELERATION CURVES

vehicles which would not be required in the same form in an electric vehicle. The assignable weight for vehicles with conventional construction is shown on line 7a and for lightweight construction on line 7b.

The values chosen for the range of the electric vehicle, line 3, are on the low side of average for internal combustion powered vehicles in the case of the family car, city taxi and city bus. For the commuter car, utility car, and delivery van, we chose values which might represent reasonable daily ranges for vehicles which are not likely to be used continuously for long periods.

B. POWER AND ENERGY CALCULATIONS

Two sets of calculations are needed to define the power and energy requirements of a vehicle. First, we must know the maximum power and the velocity at which this maximum occurs. Second, we must calculate the total energy consumed when the vehicle operated under various driving conditions.

1. Power Requirements

The power expended by the vehicle can be represented by the following expression:

$$\text{instantaneous power} = \text{velocity}\ [\text{mass x acceleration} + \text{aerodynamic drag} + \text{rolling resistance}]$$

The maximum power requirement is determined by expressing all the quantities on the right hand side in terms of velocity as a variable. The expression is then differentiated and the resulting function put equal to zero.

a. Acceleration

The first step was to express the maximum linear acceleration in terms of velocity. This was done by synthesizing simple analytical expressions which fitted the graphical data reasonably well within the normalization limits of the performance curves. These expressions,* which are shown graphically in Figure 2, are as follows:

Family Car: $a = 20 - 0.500\,v + 5.3 \times 10^{-3} v^2 - 2.2 \times 10^{-5} v^3 - 8\,(1 + 10^{-3} v^3)^{-1}$

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* The symbols and units used in the analytical expressions are as follows:

a	acceleration (ft sec^{-2})	M	weight of vehicle (lb)
A	frontal area (ft^2)	S	distance travelled (ft)
C_D	drag coefficient (dimensionless)	t	time (sec)
g	gravitational constant (32.2 ft sec^{-2})	v	velocity (ft sec^{-2})

Commuter Car: $a = 7.0 - 0.028v - 1.3 \times 10^{-3}v^2 + 0.9 \times 10^{-5}v^3$

Utility Car and Delivery Van: $a = 6.6 - 0.046v - 1.3 \times 10^{-3}v^2 + 0.7 \times 10^{-5}v^3$

City Taxi: $a = 5.2 - 0.006v - 5.3 \times 10^{-3}v^2 + 7.0 \times 10^{-5}v^3$

City Bus: $a = 9.0 - 0.053v - 3.0 \times 10^{-3}v^2 + 3.0 \times 10^{-5}v^3$

From these expressions, the power expended on linear acceleration during periods of maximum acceleration can be expressed as a function of v, namely

$$\frac{Mav}{g}$$

If the power required for rotational acceleration is assumed to be 10% of that for linear, the total power used for acceleration is

$$\frac{1.1\ Mav}{g}$$

b. Aerodynamic Drag

Estimates given in the literature for power consumption caused by aerodynamic drag vary considerably. For example, using a 2000-lb vehicle traveling at 60 mph, Hoffman* finds 9.7 hp and the Morse panel** finds 17 hp. Basically, the reason for these discrepancies is varying judgments as to the practicability of employing good aerodynamic body styling. We take an optimistic view and believe that the arguments of Tenniswood et al.† are sound. These authors reason that the incentive to reduce air resistance in gasoline-propelled vehicles is comparatively weak, because no initial cost saving is achieved; in electric vehicles however, particularly those designed for high speed, it can affect first cost by reducing the battery capacity required for a given range. We believe that, compared with the problems of developing satisfactory power sources, improving the aerodynamic characteristics of vehicle bodies would be relatively easy. We have therefore employed optimistic values for the drag coefficients, C_D, in the following expression:

$$\text{Drag force} = 1.19 \times 10^{-3}\ C_D A v^2 \ \text{pounds}$$

The values assumed for frontal area, A (Table 1, line 8) reflect a moderate degree of streamlining.

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*op cit.

***The Automobile and Air Pollution: A Program for Progress,* Report of the Panel on Electrically Powered Vehicles (R.S. Morse, Chairman), U.S. Dept. of Commerce, October 1967.

†D.M. Tenniswood and H.A. Graetzel, Ford Motor Co. (SAE paper no. 670177), 1967.

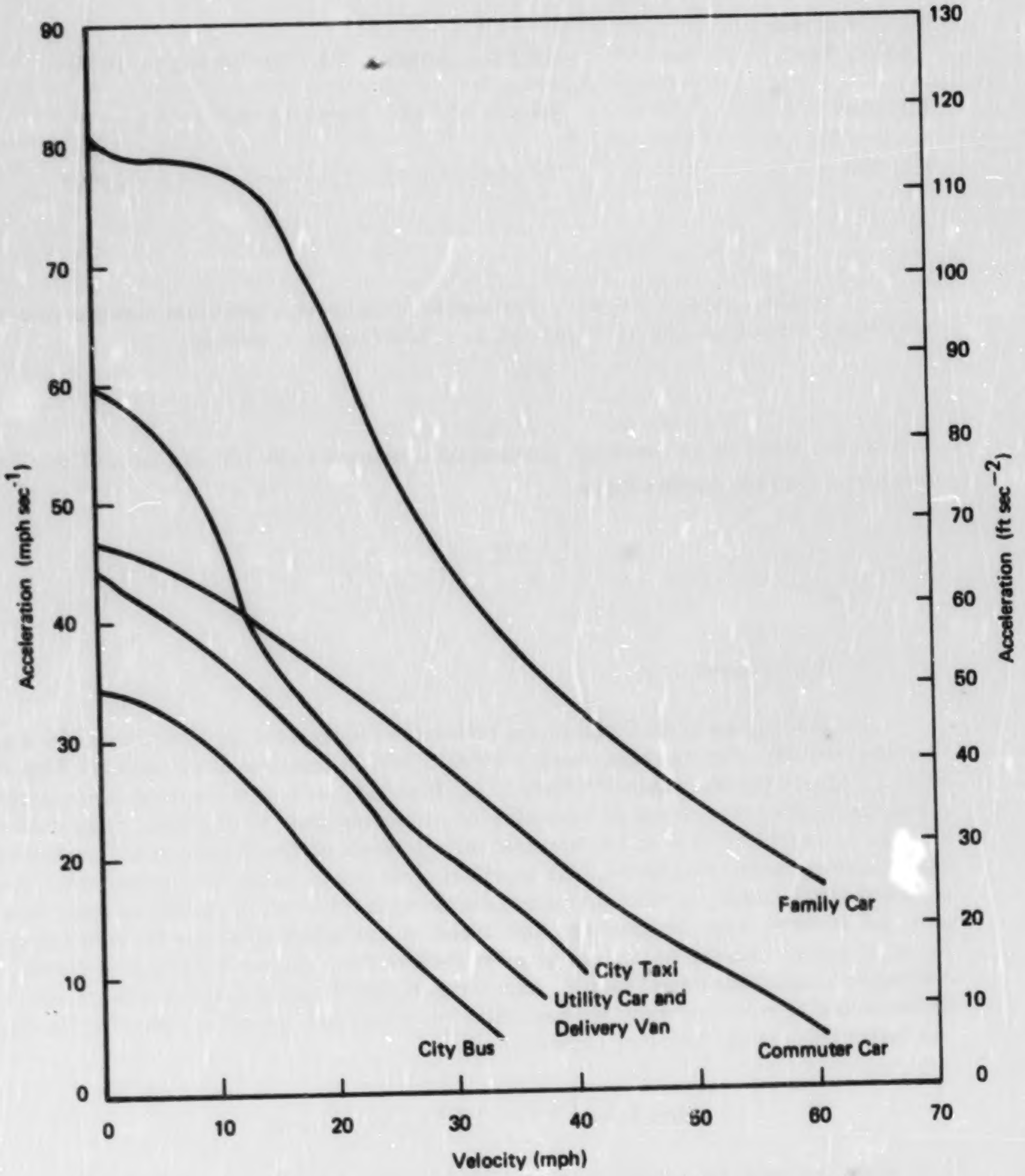

FIGURE 2 ACCELERATION VERSUS VELOCITY FOR SELECTED VEHICLES

c. Rolling Resistance

When a vehicle moves at uniform velocity over a smooth road, that portion of resistance which is not due to aerodynamic drag results principally from the work done in distorting the tires, together with a small addition from wheel bearing and gearbox friction. Some authorities, such as the Morse panel, treat rolling resistance as a constant force dependent upon tire characteristics and vehicle weight, but this does not agree with the data presented by Tenniswood et al., Hoffman, and Stiehler et al.* Combining the available data, we have derived an empirical equation relating rolling resistance to vehicle weight and speed. If the latest developments in low-loss tires are employed, the resistance would be less than the values calculated from the equation, but we have taken a cautious approach for the following reasons: 1) much of the reduction in rolling resistance of improved tires is lost if correct inflation pressures are not maintained; 2) a soft ride may be demanded by buyers of electric automobiles, and on rough roads this would require that energy be absorbed either in the tires or by the suspension system; 3) federal safety requirements for tires cannot at present be met by tires with very low rolling resistance.

Our empirical expression for the rolling resistance, which also includes the losses in the gearbox and bearings, is:

$$\text{Rolling resistance} = \frac{M}{50}\,(1 + 1.4 \times 10^{-3}v + 1.2 \times 10^{-5}v^2)\ \text{pounds.}$$

d. Calculations of Maximum Power

The final expression for instantaneous power under conditions of maximum acceleration is thus:

$$\frac{v}{550}\left[\frac{1.1\,Ma}{g} + 1.19 \times 10^{-3}\,C_D A v^2 + \frac{M}{50}\,(1 + 1.4 \times 10^{-3}v + 1.2 \times 10^{-5}v^2)\right]\text{horsepower}$$

where a is related to v by the expressions given above in subsection a and the factor 550 converts ft lb $\sec^{-1}$ to horsepower. This expression is plotted in Figure 3 for the family car. In this case the total power requirement does not pass through a maximum value in the velocity range of 0-60 mph, and the conditions for maximum power are those for maximum acceleration at 60 mph. A number of the other vehicles show maxima at velocities in the 20-40 mph range. Values for the maximum power, which is that delivered at the output of the gearbox, are shown in line 11 of Table 1.

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* R. D. Stiehler, M. N. Steel, G. G. Richey, J. Mandel, and R. H. Hobbs. *J. Res. Nat. Bur. Std.*, Vol. 64 C, 1960.

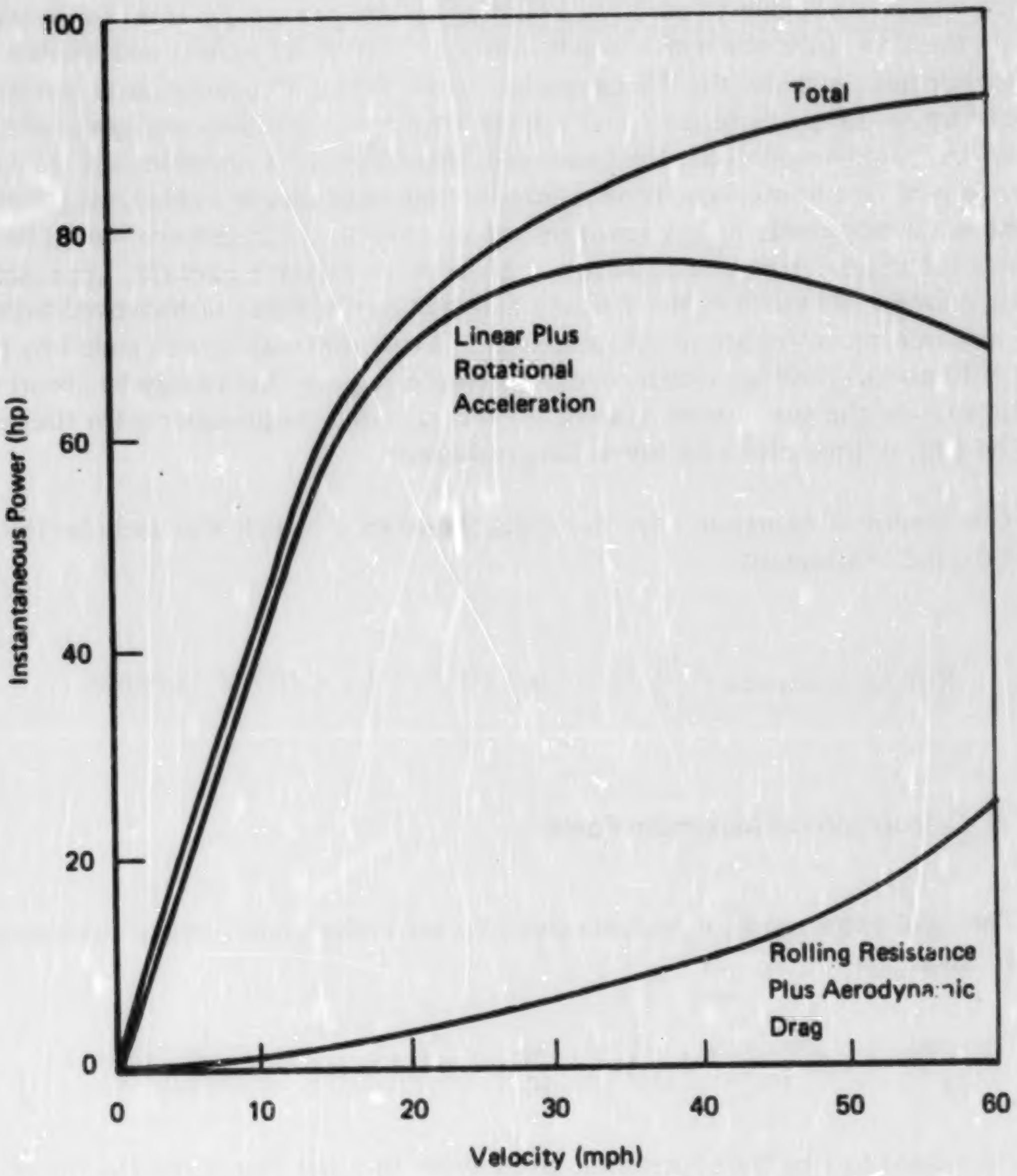

FIGURE 3 POWER REQUIREMENTS FOR THE FAMILY CAR AT MAXIMUM ACCELERATION

2. Energy Requirements

The energy requirements for each vehicle, corresponding to the values for the range, listed on line 3, are heavily dependent upon the driving cycle or pattern of use involved. Thus, for a given quantity of energy stored, the range of an electric vehicle operating nonstop at constant velocity might be several times that when operating in city traffic with frequent stops.

The selection of an appropriate driving cycle is somewhat arbitrary. After consultation with representatives of the National Center for Air Pollution Control, we have adopted, for all vehicles except the city bus, the "Public Health Service Cycle" derived from a driving cycle (LA4) based on studies in the city of Los Angeles. This cycle is set out in Table 2. For the city bus, another cycle was devised which reproduces the statistical observation that its average velocity is 12 mph and that it makes ten stops per mile; this cycle is shown in Table 3.

On the basis of these driving cycles and the assumed parameters for the vehicles, we calculated the delivered energy requirements for the various ranges. These are shown on line 14 of Table 3. The requirements for stored energy, line 15, were derived by dividing the delivered requirement by the electric transmission efficiency.

C. ELECTRIC TRANSMISSION PARAMETERS

The weights allotted to the motors, control systems, cabling, etc. for the six classes of electric vehicles have been estimated on the basis that high-speed dc motors with silicon controlled rectifier chopper control circuits would be the most appropriate system. The factors affecting this choice are considered later, in Section IV. This subsection contains details of the specifications for the various components of the electrical transmission for each class of vehicle.

One of the fundamental characteristics of electric motors and electromagnetic machines in general is their ability to deliver a constant torque over their entire speed range. By proper control, a motor can be made to deliver its rated torque or fraction thereof at any speed from zero up to the physical limit of its rotating member. By overloading the motor, one can produce 150% to 200% torque for short periods of time; the amount of overload torque obtainable and the length of time the motor can deliver it without damage depend on the details of the design of its motor particularly as it affects thermal capacity. Since horsepower is the product of torque and speed, the maximum horsepower from a given size motor is obtained by operating it at its highest speed. The rated maximum speed is dictated by the mechanical stress limit of the rotor. These fundamental motor relationships are summarized in Figure 4.

TABLE 2

PUBLIC HEALTH SERVICE CYCLE

Velocity Mode (mph)	Mode Time (sec)	Cumulative Time (sec)	Acceleration Rate (mph/sec)
0	30	30	–
0-19	8	38	+ 2.38
19	15	53	–
19-44	12	65	+ 2.08
44-52	7	72	+ 1.14
52	9	81	–
52-37	12	93	– 1.25
37	16	109	–
37-31	5	114	– 1.20
31-0	13	127	– 2.38

TABLE 3

CITY BUS CYCLE

Velocity Mode (mph)	Time (sec)	Distance (ft)	Acceleration Rate (mph/sec)
0-15.7	6.60	76	+ 2.4
15.7	13.30	306	–
15.7-19.0	1.35	35	+ 2.4
19.0-0	7.95	111	– 2.4
	29.2	528	

Average speed = 12.2 mph

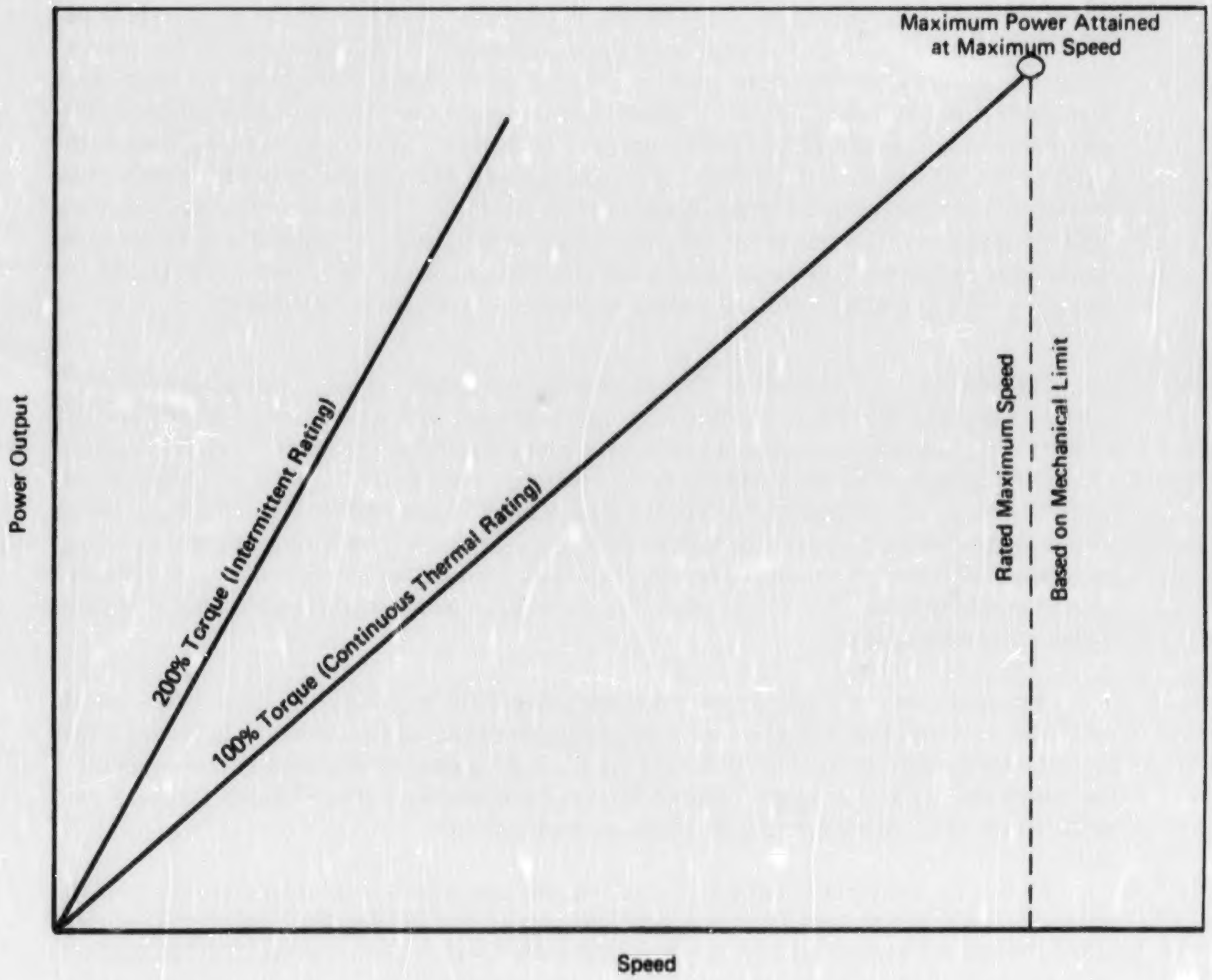

FIGURE 4 POWER-SPEED CHARACTERISTIC CURVES FOR ELECTRIC MOTOR

The selection of one or more motors for a given vehicle application involves matching motor characteristic curves of the type shown in Figure 4 to the power demand profile for the vehicle, such as that for the family car in Figure 3. This matching is shown in Figure 5 where the dashed line represents the characteristics of the smallest dc motor which could meet the power requirements entirely within its rated power capabilities. Since maximum power demand will in practice be relatively infrequent and of short duration, one could safely select a motor which would have these capabilities on 100% overload. The power-speed relationship for the chosen motor is shown by the solid sloping line. It can be seen that the maximum power output of which this motor is capable and which is attained at its maximum motor speed will be significantly greater than the maximum power demand of the vehicle. The vehicle cannot, however, use a smaller motor because of its need for substantial power at lower speeds and cannot utilize the full capability of a larger motor because of the limited output of the power source. A smaller motor could be used if a gear changing mechanism or torque converter were inserted into the power train, but such devices are undesirable because they introduce extra weight, cost, and power inefficiency.

The selection of motors is also influenced by certain general engineering considerations. For example, we have chosen to use a motor for each wheel in the family car, delivery van, city taxi, and city bus (the latter being a six-wheel vehicle); this has been done to obtain certain benefits resulting from separate control of the power applied to the individual wheels.* Normally, the use of several small motors rather than one large motor would incur a weight penalty: for motors of a given speed, the power output per unit weight increases with increasing size, since magnetic and thermal designs become more efficient. This characteristic can be offset, however, by designing the smaller motors to operate at higher maximum speeds.

Estimates of the weights of these high-speed dc motors have been based on dc machines now used in aerospace and torpedo propulsion applications. It is assumed that these motors would be cooled by forced air from a separate blower system. The weights of the controllers have also been estimated from existing devices, some of which are being used in lift trucks and other electric motor control applications.

To size the controllers and vehicle cabling, we have had to make assumptions about the maximum voltage for the electrical system in each of the vehicles. The values selected were 500 volts for the family car and city bus, 250 volts for the commuter car, delivery van, and city taxi, and 125 volts for the utility car. Allowance has also been made for the weight associated with the electric cabling, component mounting, cooling system, and a speed reducer for each motor-wheel system.

Estimates based on the present state of the art have also been made for the efficiency of the individual motors and controllers. Speed-reducer efficiencies were already considered in the calculation of energy requirements.

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* A compromise of two wheels per motor was made for the commuter car and the utility car.

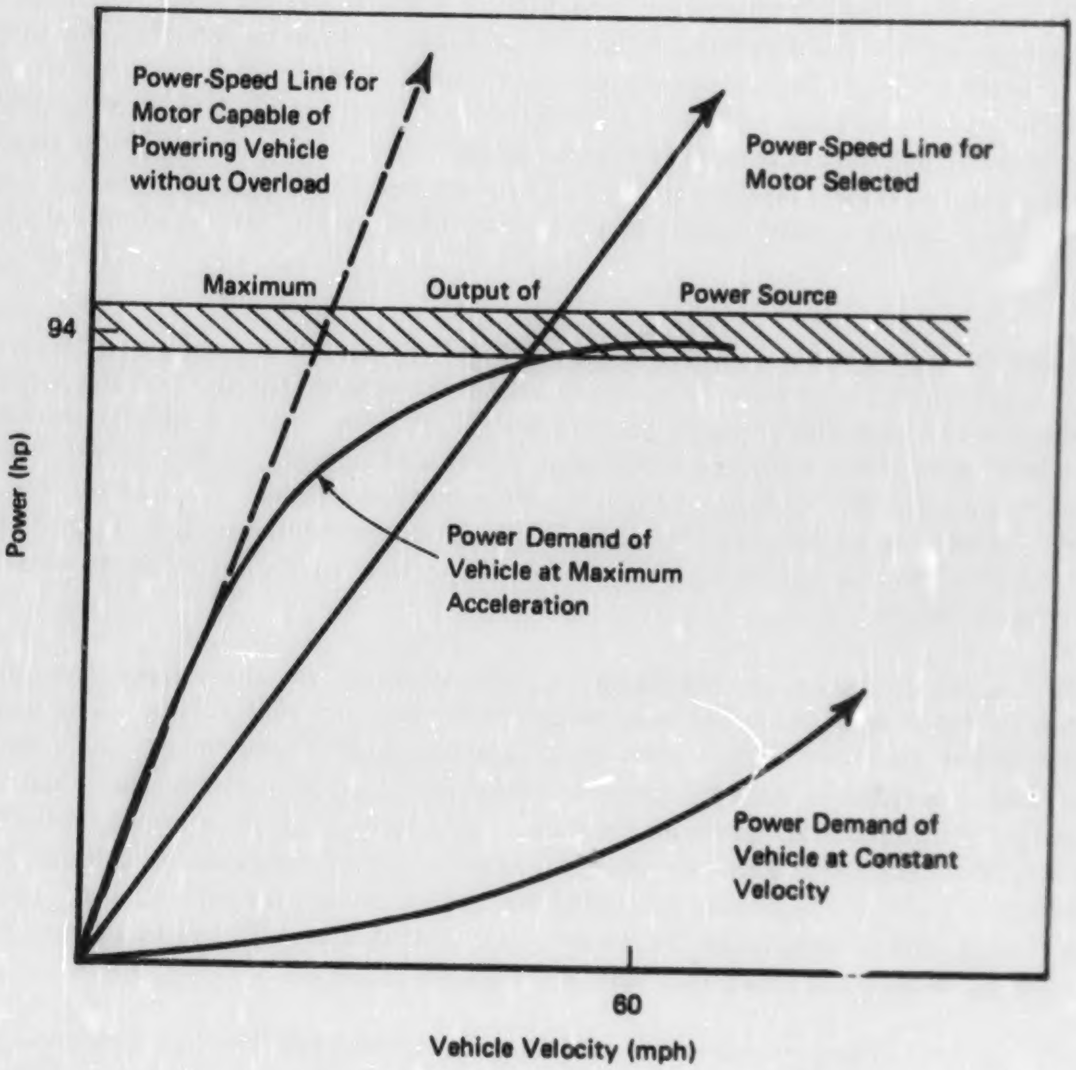

FIGURE 5 MOTOR SELECTION FOR FAMILY CAR

The results of these analyses are presented in Table 4 and the total weight of the electric transmission system is entered in line 16 of Table 1. It can be seen that this weight amounts to some 5-6% of the curb weight of all vehicles except the family car (for which it is about 10%) and the city bus (about 3%). The effects of matching the motor to the profile of vehicle power demand can be seen by comparing the estimates for the maximum possible output of the motors in the family car (56 hp) with the maximum actually used (23.5 hp). Each motor thus has a potential output of 1.0 hp per lb but a useful output of only 0.41 hp per lb.

From the values for electric transmission weight presented in Table 4 and included in Table 1, line 16, it is possible to estimate allowable weights for the power source by subtraction from the weights given on lines 7a and 7b of Table 1. The results are shown on line 17. Combining these with the calculated power and energy demand of the vehicle enables us to calculate the required energy densities and power densities for power sources capable of meeting the vehicle specifications. These values are entered on lines 18 and 19 of Table 1 and form the background to the review of the state of the art in electrochemical power sources in Section V.

The approach taken in this study focuses attention on the energy and power capabilities of the power source per unit weight rather than per unit volume. The justification for this is that the average densities of electric motors, controllers, and electrochemical power sources are, with the possible exception of ambient-temperature fuel cells, fairly similar to those of the components they would replace in an internal-combustion-powered vehicle. Moreover, since the electrical system is interconnected by cabling rather than mechanical links, it has greater flexibility for location within the vehicle. Thus it seems reasonable for a first consideration to assume that w-hr/lb and w/lb can be used as yardsticks of the technical merit of a power source for vehicle applications.

The analysis of power and energy requirements carried out here has been concerned only with the demands of the vehicle for mechanical energy. Present-day automobiles use significant amounts of energy for a variety of other purposes. Most prominent are the demands for heating and air conditioning, the former amounting to a maximum of perhaps five thermal kilowatts and the latter to two electrical kilowatts in the average family car. The additional demand for lights and various ancillary power equipment can amount to a sizable fraction of a kilowatt. In our analysis we have neglected these demands, since an auxiliary gasoline-fed burner is probably the most appropriate type of heating device, and air conditioning is not yet regarded in most of the United States as a necessity.

TABLE 4

ELECTRIC TRANSMISSION PARAMETERS

		Family Car	Commuter Car	Utility Car	Delivery Van	City Taxi	City Bus
Maximum power delivered to wheel speed reducers	(hp)	94	30	16	66	48	180
	(kw)	70	22	12	49	36	135
Number of motors		4	2	2	4	4	6
Maximum power delivered to wheel speed reducers by each motor	(hp)	23.5	15	8	16.5	12	30
Maximum motor speed	(rpm)	13,000	16,000	19,000	16,000	16,000	12,000
Fraction of maximum motor speed at which motor delivers its maximum power* to the wheel speed reducers		0.42	0.48	0.56	0.48	0.42	0.42
Maximum power output of which each motor is capable at its maximum speed	(hp)	56	31	14.5	34.5	28.5	71.5
Weight of motors	(lb)	4 x 57 = 228	2 x 33 = 66	2 x 18 = 36	4 x 36 = 144	4 x 32 = 128	6 x 70 = 420
Motor efficiency	(%)	88	85	80	85	83	90
System voltage		500	250	125	250	250	500
Weight of controller	(lb)	50	30	28	66	48	90
Controller efficiency	(%)	93	91	90	93	92	95
Weight of speed reducers	(lb)	15	6	3	12	8	30
Weight of cables, mounting, etc.	(lb)	45	12	12	30	20	60
Weight of cooling system	(lb)	10	4	3	7	6	15
Overall efficiency (excluding speed reducers)	(%)	82	77	72	79	76	85
Overall weight of electrical system (including speed reducers)	(lb)	348	118	82	259	210	615

*Assuming 100% overload capability.

IV. ELECTRIC TRANSMISSION SYSTEM

This section discusses the state of the art of electric transmission systems as it applies to the criteria for the vehicle classes arrived at in Section III.

The function of the electric transmission system is to drive and control the speed of the wheels of the vehicle, using the power of the battery, fuel cell, or hybrid power source. The system consists of one or more motors geared through speed reducers to the wheels of the vehicle, a control unit for each motor, and electric cables that join the control units to the power source. Since the control units, motors, and speed reducers have certain unavoidable losses, the resulting heat must be dissipated by a cooling system, the weight of which must be assigned to the electric transmission system.

In a battery-powered vehicle, it is extremely important to have high efficiency throughout the electric transmission system, since battery power is limited. Replacement of the automatic transmission with a fixed-ratio speed reducer increases the overall efficiency; however, some weight penalty is imposed upon the motors, since they are called upon to deliver high torques at extremely low speeds. This weight penalty is not too severe if high-speed motors and large speed reduction ratios are used, as discussed in subsequent sections.

A. MOTORS

The maximum rated speed of a motor depends upon the rotor construction, which varies with the type of motor. The most important limitation is the rotor peripheral velocity; this is determined by the speed and the rotor diameter, as shown in Figure 6 for four types of rotor construction. Obviously, the smaller the diameter, the higher the allowable rotor speed.

For the low-horsepower requirements of small vehicles, motors of relatively small diameter can be used, and thus very high rotor speeds are possible. This helps to counteract the intrinsically greater efficiency of large motors: by operating the low-horsepower motors at higher speeds than the high-horsepower motors, one can largely avoid the penalty in pounds per horsepower imposed upon smaller machines. Further significance of the information contained in Figure 6 will be discussed when the relative advantages of ac and dc motors are discussed later in this section.

Since high speed is a requirement for obtaining a high horsepower per pound, it is desirable to have a small diameter and hence a long rotor. At the present state of the art, therefore, only conventionally shaped, cylindrical-rotor dc and ac motors capable of high-speed operation can be considered for vehicle propulsion.

The two unconventional dc motors described below are discussed for the sake of completeness but must be excluded from vehicle use consideration at this time.

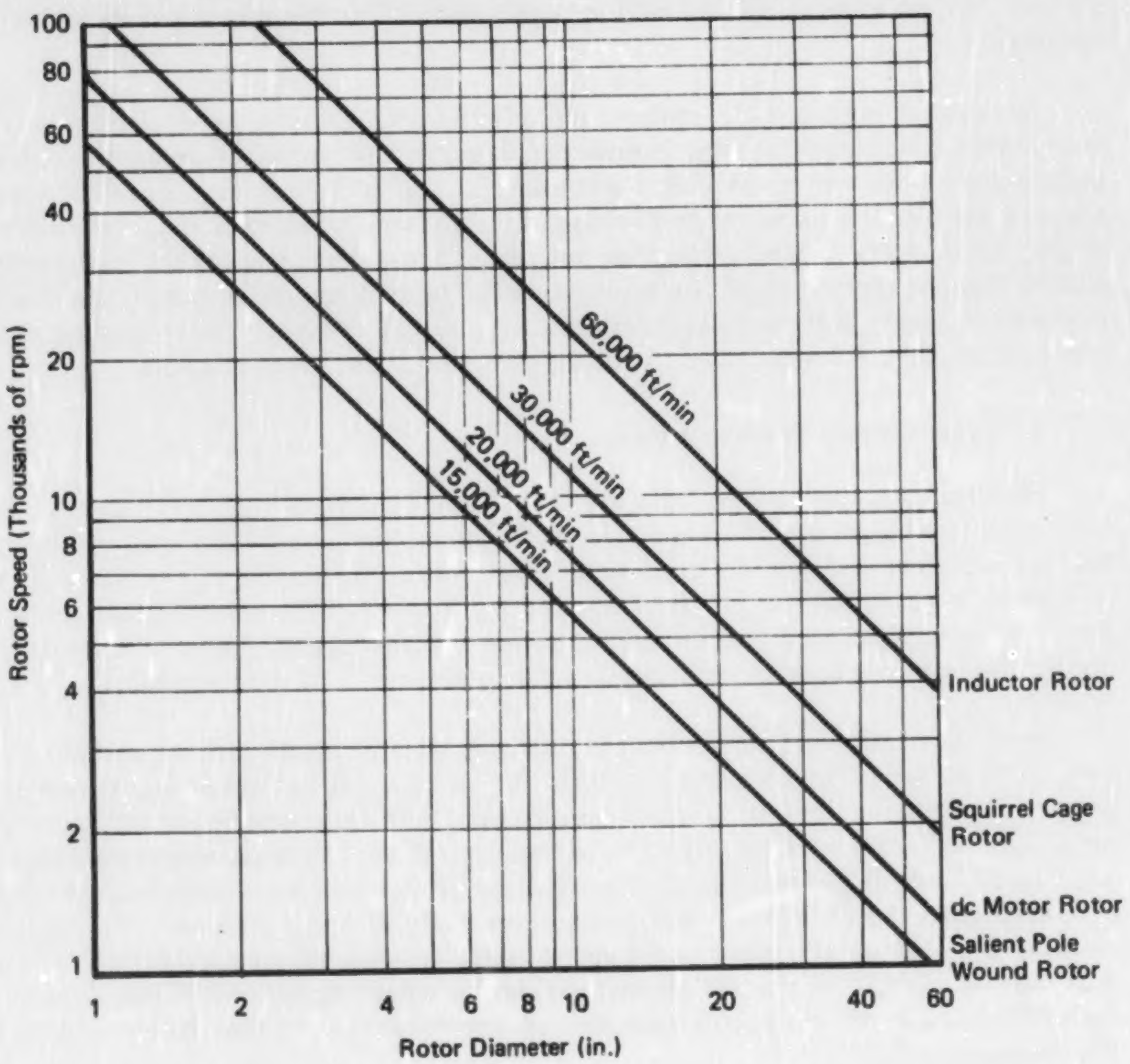

FIGURE 6 ALLOWABLE ROTOR SPEEDS

Pancake-shaped motors, of which the most common is the printed-circuit dc motor, are large in diameter and short in length; consequently they have high rotor stresses at high speeds and are not acceptable for electric vehicles. Widely used in low-inertia, fast-response drives, such motors have axial working air gaps instead of the annular gaps of conventional motors. This produces a different physical configuration, but the torque per ampere is about the same.

So-called homopolar dc motors are unacceptable because, as explained later, the characteristics of control systems do not permit use of any motor which requires extremely high currents and correspondingly low voltages. This is unfortunate, since their voltage requirement nicely matches the low voltage available from batteries. Homopolar motors also employ liquid metal brushes, which do not permit the maximum speed that is theoretically possible for the type of rotor construction used. The only appreciable application of these machines has been in homopolar generators; these supply extremely heavy currents at a few tens of volts and are desirable because of the smooth dc power they generate.

1. Direct-Current Traction Motors

Direct-current motors have been used for a number of years in electric locomotives and have established a good performance record. These motors have carbon brushes and copper bar commutators and are of series field construction. In this form of construction the armature current establishes the field flux; proper control of the armature voltage provides high torque at low speed and decreasing torque at higher speeds. Thus, an approximately constant horsepower characteristic can be achieved over most of the speed range.

Since dc traction motors are built in relatively large sizes with high horsepower ratings, they are not usable in their present form for electric vehicle propulsion. However, the general design technology of traction motors for electric locomotives is adaptable to the production of reliable dc motors for electric vehicles. Present traction motors have relatively large rotors and do not operate at the high speeds required for electric vehicles, but the peripheral velocities of the rotor and commutator establish design guidelines for scaling. It is customary to have a maximum rated speed which corresponds to commutator peripheral velocities of 12,000 ft/min, with overspeed during wheel slippage of 20,000 ft/min. This corresponds to rotor peripheral velocities of approximately 15,000 ft/min and 25,000 ft/min, respectively.

Direct-current traction motors have also been applied to fork lift trucks, delivery vans, and golf carts. In these applications cost did not justify developing the lightest and highest speed motor. Instead, the selection was based on available electric equipment. Therefore, these applications do not represent attempts to extend the state of the art.

The applications where effort has been made to obtain the maximum horsepower per pound are in electric torpedo propulsion and aircraft dc generators and motors; even these do not represent the ultimate, however, because their speed is restricted by the nature of the systems in which they are used. If motors for vehicles were designed like these special motors and run at speeds approaching their maximum rated values, they could deliver about one horsepower per pound, at least in the larger sizes.

The effect of speed is illustrated in Figure 7. For a given increase in horsepower per pound, it can be seen that the speed of a small motor must be increased more than that of a large motor. Fortunately, for the range of vehicle horsepower considered in this study, the necessary speeds (12-19,000 rpm; see Table 4) are within the capabilities of today's bearings. The accompanying stresses are within the rated design values, and reasonable brush wear is maintained.

It must be emphasized that the values plotted in Figure 7 are based on the motors' maximum horsepower rating – i.e., the horsepower they can deliver at their maximum rated speed and torque. Normally, aircraft dc generators are not rated in this manner, so published specifications must be carefully interpreted.

Because of the high performance which can be obtained from dc motors and the ease with which they can be controlled, they are currently being used in small electric vehicles and in larger experimental vehicles. In general, they provide a very acceptable interim solution to the electric transmission system. To obtain higher horsepower per pound and eliminate the brush wear problem of the dc commutator motor, however, an ac motor must be used.

2. Alternating-Current Induction Motors

In an induction motor, the rotor is a squirrel-cage arrangement of conductors imbedded in steel. This robust construction permits a high rotor speed (see Figure 6). In addition, the active length of the rotor can be longer than that normally used for a dc commutator motor. These features enable an ac induction motor to have a higher horsepower per pound.

Since the induction motor requires alternating current and the battery provides direct current, one of the functions of the control unit is to act as an inverter, controlling the speed of the motor by varying the frequency of the ac power. The control unit must also provide the proper voltage-to-frequency ratio to enable the motor to deliver its rated torque over the entire speed range. The resulting torque vs speed curve differs greatly from that normally associated with an induction motor; however, it is completely consistent with the principle that any electromagnetic machine is capable of constant torque over its entire speed range.

Induction motors for vehicle propulsion are similar in construction to high-performance aircraft motors of the low-slip variety. Such motors have low-resistance rotors that minimize losses. Normally, low-slip designs would be unsuitable because of their high starting currents; with a current-limiting control, however, starting current is not a problem, and the motor design can be optimized for maximum efficiency.

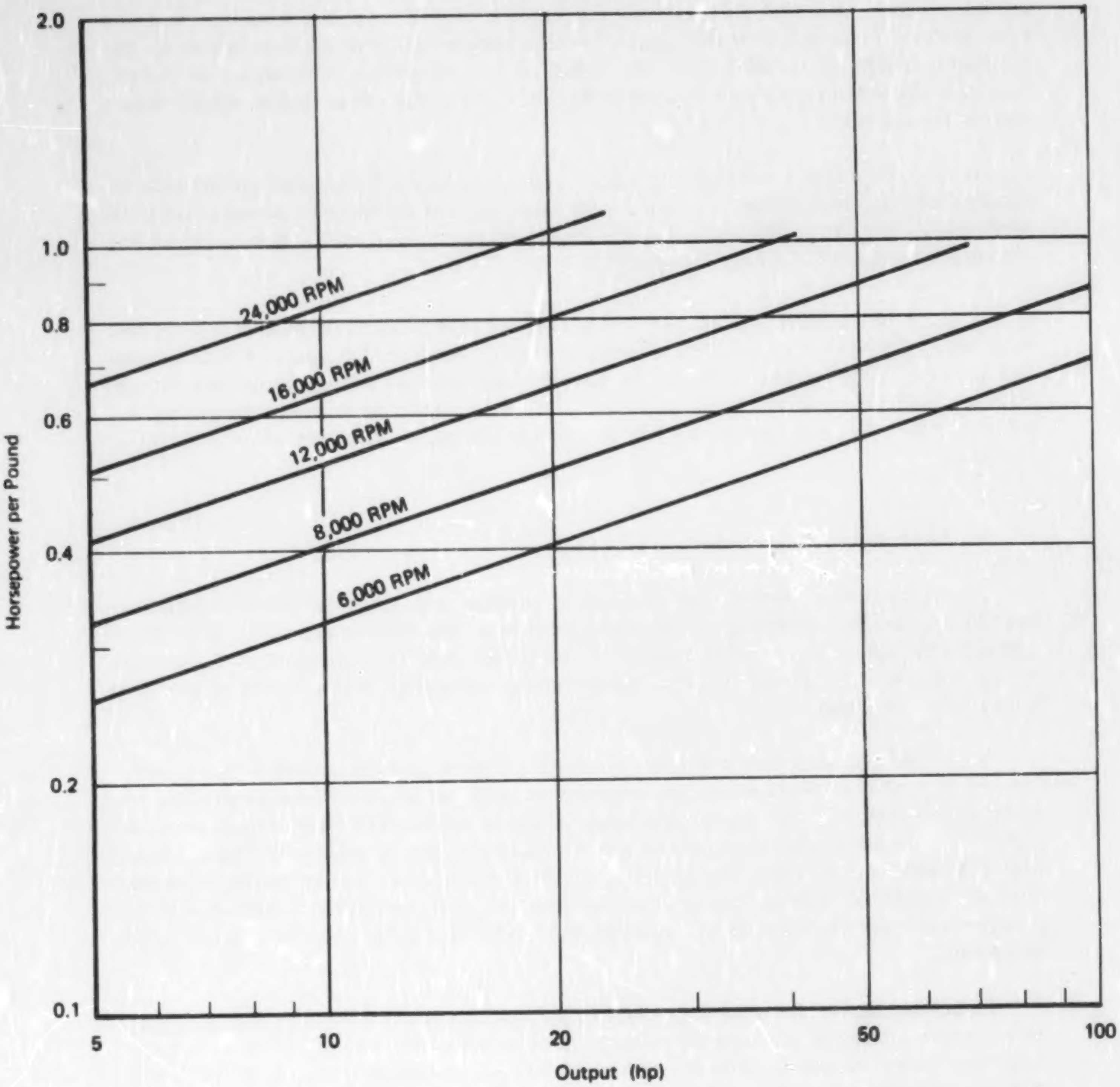

FIGURE 7 WEIGHTS OF DC MOTORS

Recent experimental electric vehicles and rapid transit systems have used induction motors. By taking maximum advantage of their desirable characteristics, manufacturers have been able to build induction motors that provide approximately two horsepower per pound. (This is based on the horsepower at maximum rated speed; induction motors generally lack the overload capability of dc motors, so the figure is an estimate based on 200% overload capability for five minutes.) Figure 8 includes data on two recently publicized induction motors.

Since the above applications have used induction motors of high horsepower, speeds exceeding the 13-19,000 rpm range have not been necessary. It is doubtful that a high horsepower-to-weight ratio could be maintained for lower-rated motors by increasing their speed, because bearing problems would be encountered. However, the use of induction motors eliminates brush wear at the expense of some increase in control unit weight and cost; this advantage will be further discussed later.

3. Synchronous Motors

The synchronous motor is another possible contender for powering future electric vehicles. In this type of motor, ac power is supplied to the stator to produce a rotating magnetic field, and the rotor revolves synchronously with the field. The most common design has a "wound field" – i.e., excitation current is supplied to the rotor through slip rings and creates strong north and south poles in passing through the rotor windings. While such a motor must have brushes to make connection with the slip rings, the brush wear is far less than with the commutator of a dc motor.

Nevertheless, a truly brushless motor is desirable because brushes are a possible source of trouble. The simplest form of brushless synchronous motor uses permanent magnets in the rotor and, therefore, needs no brushes, but its power output is too low for vehicular applications. A promising recent development is the solid-rotor brushless machine; much work has been done on this design for aerospace generators, and various experimental units have been built. These have characteristically been heavier than comparable motors of wound-field construction, but they have the offsetting ability to be run at higher speeds. This advantage cannot be fully utilized in small motors for the lighter vehicles, because their bearings cannot withstand the speeds permitted by the rotor. (Sophisticated, high-performance bearings are too expensive for the uses considered here.) The speed capability of the solid rotor might, however, prove advantageous for applications in vehicles such as buses that require larger, more powerful motors.

The principal advantage of synchronous motors over induction motors is that the former require a lighter, less complex control unit. Synchronous motors receive rotor excitation power directly from the battery; their control units supply power to the stator only. Induction motors, on the other hand, obtain excitation power from the control unit via the stator circuit. As a result, their control units must be more powerful and thus heavier. Furthermore, to prevent excessive heating of the battery, they must provide storage for the excitation power that cycles back and forth from the motor. This storage usually takes the form of a capacitor bank across the battery terminals, which involves a further weight increase.

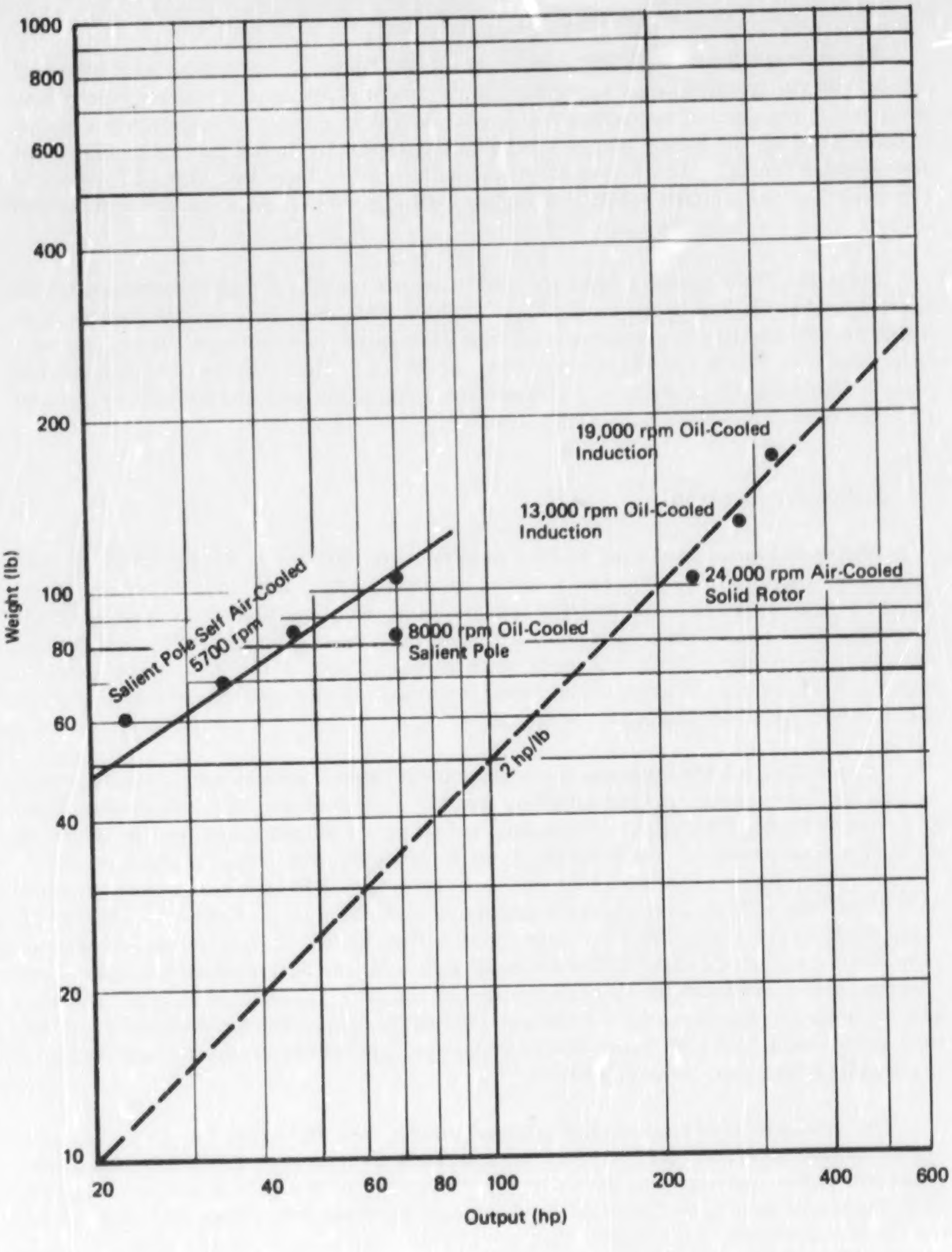

FIGURE 8 WEIGHT VERSUS POWER OF AC MOTORS

Because of this advantage of the synchronous motor over the induction motor, it would be desirable to use synchronous motors. Until the brushless variety is fully developed, the slip-ring, wound-field synchronous motor is perhaps the most desirable solution for powering an electric vehicle, if the higher control cost of the ac motor approach can be justified.

The synchronous motors which might be used could be patterned after aircraft generators. As with aircraft dc generators, the technology is highly developed and is directly applicable to air-cooled and special oil-cooled machinery. The weights of a few standard aircraft generators with slip-ring-fed rotors are shown in Figure 8 when rated as motors. Also shown is the weight of a solid-rotor machine developed for a high-speed application.

The cost of high-speed air-cooled or oil-cooled motors with integral gear reducers cannot be closely estimated from available data; the requirements for aerospace applications differ greatly from those for mass-produced electric vehicle drive motors, even though speeds, ratings, and technologies are similar. As a rough estimate, the manufacturing cost in large quantities of motor and gear reducer might ultimately be about $4 per vehicle horsepower for a dc commutator motor. For an ac induction motor, it might be as low as $2 per vehicle horsepower. The cost of solid-rotor synchronous motors would range between these limits, approaching the upper figure for those of higher speed.

B. CONTROLS

Historically the speed of dc traction motors has been controlled by inserting a resistance in series with the motor so as to regulate the current from the dc power source. In addition to switching resistance into and out of the circuit, switching of the field circuit between series and parallel connection is also customary. This manner of speed control causes jerky performance and is inefficient from the standpoint of conserving battery power.

Because a battery supplies an essentially fixed dc voltage, and because the speed of a dc machine varies with the input voltage, a control must be used that will effectively vary the voltage with negligible losses. The advent of solid-state devices has made such control possible. Instead of reducing voltage by inserting resistance into the circuit, these devices achieve the same effect by rapidly interrupting the current. The longer the interval of disconnection, the lower the average voltage that the motor receives. The motor current is not interrupted during the time that the battery is disconnected; rather, the motor circuit is closed on itself.

The switching elements which are used to disconnect the motor winding from the power source are silicon power transistors or silicon controlled rectifiers (SCR's). The difference between them is that SCR's can be turned off only by reversing their anode-to-cathode voltage for a short time; silicon power transistors can be shut off simply by interrupting their control current. Both devices are turned on by applying a low-power pulse to their control terminals. In the case of the power transistor, the low-power pulse must persist for the duration of power conduction. Power transistors were initially used, but SCR's are now preferred because of their higher power handling capability, even though they require special turnoff circuits. Both devices have essentially unlimited life.

1. Chopper for Direct-Current Motor

Frequently the control for a dc motor is termed a chopper, since it connects the battery to the motor intermittently. As explained above, the rapid interruption is timed to achieve the desired average voltage. A number of different schemes are possible: some use a fixed on-time with variable off-time, while others use a variable on-time and a fixed off-time; still others use a combination of these two. In general, it is desirable to operate at the highest possible chopping frequency so as to minimize the fluctuation of current; some compromise must be made, however, to reduce switching losses.

The chopper is not only much more efficient than the switch resistor type, but it also permits very exacting control of current. This, in turn, permits continuous, stepless torque control. Probably more important, the current can be limited to protect the motor and the solid-state controls themselves; with proper current limiting, high reliability can be expected from the chopper and motor. For example, if maximum torque is required from the motor, the current limit can be set at, say, twice rated motor current. This will enable the motor to deliver approximately twice its rated torque. Both the motor and control should be designed to withstand this current for perhaps 5 minutes; in this way, both the motor and the control are protected even if the motor is stalled.

The 5-minute rating of the motor is an arbitrary figure. It could be designed to be 1 or 2 minutes or even 10 minutes. The particular design will depend upon the overall system efficiency, weight, driving pattern, etc. However, the solid-state component in the chopper must be capable of carrying the overload current continuously, since its overload capability is extremely limited. Most of the other components in the chopper, except those that have a thermal storage capacity, must also be able to carry the overload current on a continuous basis.

In principle, the efficiency of the controller can be extremely high, since the process is basically lossless. However, when the SCR is carrying current, it exhibits a 1-volt drop, which when multiplied by the current gives the forward conduction loss. In addition, there are switching losses, blocking losses, and losses associated with the free-wheeling diode that closes the motor on itself during the times that the SCR blocks the current from the battery to the motor. Other losses are associated with the turnoff capacitor and its associated charging circuitry.

The efficiency of the chopper is greatly affected by the voltage of the system, because conduction loss due to the 1-volt drop is relatively less at higher voltages. Considering this loss alone in the case of a 12-volt system, the efficiency cannot exceed 92%. When the other losses are included, a rather low overall efficiency would result. Therefore, it is essential to use a high system voltage.

High voltage is important not only for increasing efficiency, but also for reducing the weight of the chopper. The physical size of the solid-state components is dependent upon the current and is unaffected by the voltage. This independence of voltage does not hold for the capacitive and inductive components in the chopper, however; their size and weight are in general related to the power handled and also to the precise design of the chopper.

As a rule, it is best to use as high a voltage as possible to reduce the magnitude of the current. To keep the rated current below 100 amperes and hence the overload current below 200 amperes, it is necessary to use voltages of the order of 150-500V for the range of vehicles studied. For these voltages the weights which should be achievable are shown in Figure 9. These weights assume fan cooling of the choppers, which is possible because of their high efficiencies (90% or more). Heavy contactors and circuit breakers should not be necessary, because of the current-limiting capability of the chopper.

Considering the small size of the chopper, it might be feasible to attach it directly to the motor housing. In this way, dissipation of heat from the solid-state power handling components could be increased, and heavy-current carrying terminals could be avoided. This concept is analogous to the incorporation of silicon diodes within the housing of present automobile alternators.

Although the basic principle of the chopper is well understood, the device has only recently been applied to experimental fork lift trucks, delivery vans, and other vehicles. The technology is available, but it will require a great deal of development to bring the chopper from a promising concept to readily available equipment for electric vehicles.

The present manufacturing cost of a chopper control is about $20 per vehicle horsepower. However, considering the actual material costs and the fact that the manufacturing processes lend themselves to automation, an order-of-magnitude reduction to $2 per horsepower would appear to be reasonable.

All the logic functions associated with the timing and control of the chopper could be done with microelectronic integrated circuit modules. These are incredibly small and can perform many control functions at an extremely reasonable cost. Therefore, it would seem that a great deal of ingenuity and development should be directed toward applying chopper technology to a mass-produced, reliable, low-cost product.

To accomplish regenerative braking, all that is necessary is a slight rearrangement of the basic power handling component and a small amount of additional logic. Regenerative braking is only beginning to make an appearance in chopper circuits, and much innovation is needed; e.g., through appropriate current sensing and making the circuit changeovers at current zero, it would be possible to do away with all the large contactors or dc current interrupters which are frequently incorporated in choppers.

Highly efficient regenerative braking can permit the return of power to the battery. The amount returned depends upon the driving power of the vehicle as well as circuit design and efficiency. For vehicles such as buses that make frequent starts and stops, it has been

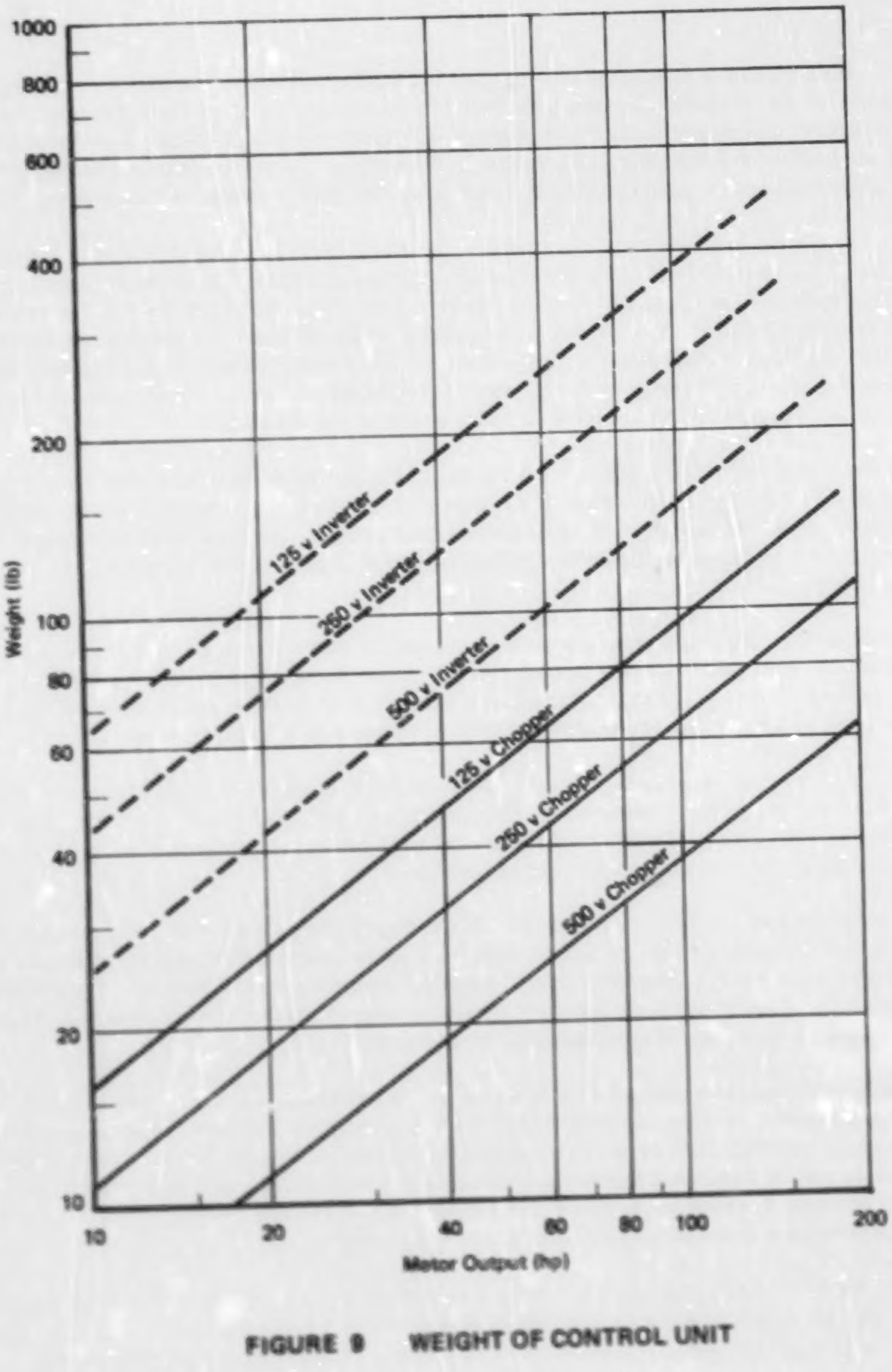

FIGURE 9 WEIGHT OF CONTROL UNIT

reported that the saving in power can be as much as 30%. For vehicles that use a more normal driving pattern, however, the energy saving is not large enough to justify the cost of adding this feature.

Regenerative braking does not make conventional brakes unnecessary, for it is of little use at low speed; most of the power is returned during the initial period of deceleration.

2. Inverter for Induction Motor

When an induction motor is used as a propulsion means, an inverter is used as the control for varying its torque and speed. An inverter takes dc power from the battery and changes it to ac power of the appropriate voltage and frequency; thus, it combines the voltage-adjusting function of the chopper with an ability to vary the frequency as well.

Inverters using SCR's for driving induction motors over wide speed ranges are relatively new. They are just coming onto the market for industrial variable-speed drives and have been used with a few experimental electric vehicles.

As with the chopper, power SCR's are used in an inverter to connect the three motor windings to the battery on a time-varying basis. In essence, at least three choppers are required, one for each of the three phases of the motor, because each phase must be cyclically energized and each carries the same peak current. In practice, it is often convenient to use essentially six choppers, each capable of delivering half the required voltage. As with the chopper, the peak current is the limiting factor in design.

In addition to all the components associated with a chopper, a large bank of capacitors must be placed across the dc input. This results from the fact that reactive power must be handled by the inverter. A further component which must be added is a special speed-sensing tachometer. A signal from this tachometer is used to determine the frequency of the inverter.

The size and weight of an inverter are typically about three times those of a chopper of equivalent power and voltage, excluding the capacitor bank across the dc input. The estimated weights are graphically shown in Figure 9 as a function of voltage and power. A manufacturing cost of $5 per vehicle horsepower should eventually be possible, again excluding the capacitor bank and tachometer.

The fact that the inverter has a more complex logic requirement than the chopper should not increase the ultimate cost; specialized integrated circuits would be developed for vehicle inverters to accommodate all the complex functions. As in the case of the chopper, current limiting is essential and must be applied with instantaneous control to protect both the inverter and the motor, as well as to provide torque control.

If regenerative braking is considered justified by the application, it can be incorporated within the inverter at a slight increase in cost by using the motor as an induction generator. This does not require that the solid-state components be shifted around, as in the case of the chopper circuit, but only that additional logic be incorporated.

To protect both motor and inverter, the controlling of the SCR's must be timed so as to limit the rate at which power is returned to the battery.

3. Static Commutator for Synchronous Motor

As with the induction motor, the speed and torque of a synchronous motor are controlled by varying both the voltage and the frequency of the power supplied. However, the control for a synchronous motor differs somewhat from an inverter; it is called a static commutator for purposes of distinction as well as to indicate its functional relation to the copper bar commutator of a conventional dc motor. The commutator and brush assembly of a dc motor in effect chop the dc input into variable-frequency power for the motor windings; when this is accomplished by a separate static commutator, the roles of stator and rotor can be interchanged. This permits a large reduction in the current that the slip rings must carry, because the current in the rotor of a dc motor is much larger than that in the stator.

The power circuit of the static commutator is identical to that of the inverter, except that it needs no capacitor bank across the dc supply. However, the control of the SCR's is somewhat different: the position-sensing tachometer attached to the motor determines which windings should be energized at any given moment. The tachometer can take a number of forms; experimental arrangements have been employed using photoelectric detectors, Hall detectors, and reluctance detectors. The information from the position sensor is used to control the main power SCR's.

The size of the static commutator is about the same as that of the inverter. The weights given in Figure 9 and the cost of $5 per vehicle horsepower also apply for the basic static commutator; to these figures must be added the small weight of the tachometer and its associated cost.

C. SPEED REDUCERS

To couple a high-speed motor to the wheel, a speed reducer with a relatively large reduction ratio is needed. For railroad traction, a gearbox with a low reduction ratio is used; these are very rugged but heavy units. At the other extreme, very lightweight gearboxes have been developed for torpedo propulsion systems, but these are designed for short life and thus are not suitable for vehicular use. It would seem that a compromise between these two technologies would lead to a gearbox with the desired reliability and light weight.

The large experimental electric vehicles built to date have used planetary gearboxes that are directly connected to the motor and employ oil cooling. This is a lightweight arrangement particularly suited to motors of relatively high horsepower.

Another solution is the "motorized wheel," in which the motor and gear reduction unit are incorporated in the hub of the wheel. This compact arrangement is now used in some earth-moving equipment and might be well suited to large vehicles like buses.

On small experimental electric cars, double timing belts have been used to achieve relatively high speed-reduction ratios. Belt drives are an extremely lightweight and inexpensive means for coupling the motor to the wheels.

In view of the mature technology of speed reduction devices, adapting one or more of these approaches should not be difficult. The principal task is to make a detailed analysis that will indicate which offers the lowest cost and best arrangement. For the small utility car, which would use air-cooled motors of rather low power, the multiple timing belt approach seems desirable; for the bus, the oil-cooled gearbox or possibly the motorized wheel might be preferable.

D. COOLING REQUIREMENTS

The heat losses which occur in the motor, the speed reduction unit, and the control unit must be removed by a cooling system. Air cooling, which is the simplest method, requires a constant-speed blower and duct arrangement. The more elaborate oil-cooling system requires an oil pump, heat exchanger, and other components. In both cases, the heat to be rejected would be used to warm the passenger compartment during the winter and discharged to the surroundings in warmer weather. The motor may have to operate for sustained periods at extremely low speed, so it cannot be used to drive the cooling system; the system must be separately driven.

V. ELECTROCHEMICAL POWER SOURCES

This section contains a review of the present state of the art of those electrochemical power sources, batteries and fuel cells, which have prospects of application as the prime power source in electric vehicles, together with some prognosis of their future development. Consideration is also given to the possibility of hybrid electrochemical systems consisting of battery-battery and fuel cell-battery combinations. (The possible application of batteries in mechanical-electrical systems is covered in Section VI.) The review of electrochemical power sources is organized into four subsections covering conventional batteries, batteries under development, fuel cells, and electrochemical hybrid combinations.

A. CONVENTIONAL BATTERIES

1. Lead-Acid

The lead-acid battery is the oldest of the secondary battery systems and has been in existence for over 100 years. It is also the most important system economically, accounting for about 80% of the more than $500 million annual sales of secondary batteries in the United States. While the largest proportion of these sales is for the specific application of starting, lighting, and ignition (SLI) in vehicles powered by internal combustion engines, a substantial volume is used as the power source for non-highway electric vehicles, such as fork lift trucks, golf carts, and mine locomotives.

SLI batteries are designed for float service with occasional high power discharge and are not suitable for traction service, which involves repeated deep discharge cycling. Batteries for traction applications have thicker plates and are generally of more rugged construction. Their delivered energy density is now in the range of 10-14 w-hr/lb. While high power drains cause a decrease in delivered energy, power densities of as much as 35 w/lb can be sustained for short periods.

The major virtues of the lead-acid system are its high degree of reliability (a typical lifetime of four to six years in traction service under a continuous daily cycle of full charge and discharge) at low cost (OEM prices approximate $0.25/lb for SLI and $0.50-0.60/lb for traction type batteries). While these virtues make lead-acid today's most important practical battery system for electric traction,* its low energy density eliminates it from consideration as the primary energy source for almost all of the six classes of vehicles under consideration in this study. The sole possible exception is the utility car with lightweight construction, the specifications for which are close to the upper limit of the lead-acid battery's technical capabilities.

The question arises as to the potential for improvement in the lead-acid system. Incremental advances in energy density are certainly possible, and in fact there has already been a substantial improvement (of the order of 30%) in these parameters over the last 15-20 years and this is expected to continue. For example, a major U.S. manufacturer is about to introduce a new industrial battery with an energy density of 16 w-hr/lb at a ten hour discharge rate. These advances have primarily resulted from the utilization of lighter, stronger materials for cases, improvement in the design of the plates, new grid alloys, more porous and durable separators, etc. Somewhat more radical changes are being worked on by a group in England (U.K. Electricity Council Research Centre), which is investigating improvements in capacity that might result from pumping electrolyte through the battery plates, although the extra complexity may make the scheme unattractive. Some publicity has been given in the United States to the use of traces of cobalt salts in the electrolyte to improve energy density (Electric Fuel Propulsion, Inc., see also Appendix A). The presence of cobalt in closely controlled proportions can lessen grid corrosion, thereby permitting the use of thinner plates and yielding a higher energy density; it does, however, increase the rate of shedding of active material from the plates, thus shortening battery life.

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* The extensive history of lead-acid battery use in highway vehicles, particularly in the United Kingdom, is reviewed in Appendices A and B.

With regard to power density, the maxima achieved in today's conventional lead-acid batteries are only moderately below the demands of the vehicle types as listed in Table 1. Operation at high power density does lower the energy storage capacity of the battery, however, and rapid charge and discharge raises the internal temperature of the battery and tends to shorten its life. An interesting recent development is that of a high rate lead-acid battery for pulse discharge and having "pile type" construction. This battery, being developed by Gould-National Batteries, Inc. for the U.S. Navy Electronics Laboratory, has a power density of around 60-70 w/lb and might possibly find application in hybrid electrical vehicle systems (see Sections IV-D and VI).

Thus the limitations on its energy density would seem to preclude the large scale use of lead-acid batteries as a prime energy source for highway vehicles. Much wider use of these batteries, based on their low cost, rechargeability, and availability is, however, foreseen for such applications as transportation within industrial plants, hospitals, airports, resorts, and off-highway shopping centers and communities. Anticipated advances and cost improvements in motors and control systems will also benefit electric vehicles used for these purposes.

2. Nickel-Cadmium

The salient technical features of the nickel-cadmium battery are its excellent service life, an energy density of 12-14 w-hr/lb, which is closely comparable to that of the lead-acid battery; and a power density which in certain constructions can be as high as 300 w/lb. There are two major types of nickel-cadmium batteries: those with pocket plates, which have cycle lives in excess of 3000 or so, and those with sintered plates, whose cycle lives are less than half as great but which have very high power densities. Because of its low energy density it is, like the lead-acid system, outside the scope of our primary power source specifications for electric vehicles, except perhaps for the small utility vehicle. Its high power density however makes it an attractive prospect on technical grounds for various types of hybrid power source, as will be discussed in Sections V-D, VI and VII. This is especially true of the 'bipolar' nickel-cadmium battery developed by Gulton Industries, Inc. for high discharge rate applications. This battery has very thin sintered plates attached to thin metal sheets which act as the connectors between adjacent cells. The thin electrode design permits the achievement of power densities of around 300 w/lb.

The nickel-cadmium battery has not been used in traction applications, except to a limited extent in lift trucks in Continental Europe and in a demonstration automobile in Sweden (Appendix B). The major drawback is its cost, which on a per pound basis is about five times that of the lead-acid traction battery. Since a significant part of these costs derives from the costs of nickel and cadmium, they are unlikely to fall sufficiently to change the nickel-cadmium battery's competitive position. A further argument can be raised against cadmium on the grounds of availability: supplies of the element are not great enough to support a major application in electric vehicles, and since it is a by-product of lead and zinc, its production cannot be economically expanded for its own sake. Thus the nickel-cadmium battery in any form seems unlikely to play a major role in electric vehicle development.

3. Nickel-Iron

The nickel-iron system has an energy density slightly lower than those of nickel-cadmium and lead-acid and a lifetime which can be measured in decades. It is also a very rugged battery, capable of withstanding much physical and electrical abuse. Its power density, however, is not as great as that of the nickel-cadmium system, and because of the smaller volume of production and the processing costs involved, its price structure is not significantly lower. The major reasons why the nickel-iron battery has not found greater general application are its poor charge retention and low electrical efficiency in charging, both of which characteristics lead to excessive gassing and a high maintenance requirement. Although it has found some acceptance in European lift trucks and in U.S. mine locomotives, the low energy density of the system gives it little relevance as a potential power source for electric highway vehicles.

4. Silver Batteries

There are two secondary batteries which use silver oxide cathodes: the silver-zinc system and the silver-cadmium system. The former battery has a high energy density amounting in certain configurations to about 60 w-hr/lb, and an excellent power density of as much as 200 w/lb, properties which on technical grounds would appear to make it a significant contender for many electric vehicle applications. It has, in fact, been used recently in certain experimental electric vehicles, most notably the GM "Electrovair" and the Yardney Electric converted Renault Dauphine (see Appendix A). However, the cycle life at full discharge seldom exceeds 40-50 cycles, and the high cost and relative scarcity of silver rule it out for large scale use. The 500-lb battery in the Electrovair II was reported to cost some $15,000, or $30/lb; and about 30% of the packaged weight is accounted for by silver, which now has a raw material cost of about $35/lb. Yardney Electric has suggested that the silver might be leased, but the poor cycle life is a difficult problem and lack of availability unsurmountable. Its use therefore seems likely to be restricted to demonstration vehicles and test bed evaluations.

The properties of silver-cadmium batteries are in many ways intermediate between those of nickel-cadmium and silver-zinc batteries. Their energy density of about 25 w-hr/lb and their high power density, comparable to that of silver-zinc batteries, make them marginal candidates from a technical standpoint for certain of the vehicle applications listed in Table 1. However, as with silver-zinc, high cost and insufficient availability of materials eliminate them from serious consideration for large scale use.

B. BATTERIES UNDER DEVELOPMENT

The technical parameters of the conventional batteries described in the previous subsection clearly fall short, particularly in energy density, of the requirements specified in Table 1. Since conventional batteries use materials with relatively high equivalent weights, an obvious route to improvement lies in the use of reactions which have higher energy release and employ active materials of low equivalent weight. The source of energy in all batteries is the oxidation-reduction reaction which takes place between the active materials of the positive (cathode) or oxidizing plate and the negative (anode) or reducing plate. The energy released, corresponding to the weights of these active materials alone, can be calculated and sets an upper limit for the energy density of a given battery system. In practice, when the weights of case, grids, separators, electrolyte, and supporting structures are considered, the practically attainable energy density is only some 10-20% of this theoretical maximum. Nonetheless, it is evident that the higher the energy release in the cell reaction, the higher the energy density of the resulting battery.

Prime candidates for use as anode materials in high energy density batteries are the alkali metals, in particular lithium and sodium. Their very reactivity, however, imposes some severe restriction on their mode of utilization. They cannot be used with conventional aqueous electrolytes, because of the rapid direct chemical reaction; their use is possible only in combination with nonreactive electrolytes, in particular molten salts and organic liquids. The former introduce the complication of a high operating temperature and, in many instances, severe problems in materials selection, while the latter tend to be hampered by low electrolytic conductivity, poor shelf life, and cathode polarization problems, which limit their power density.

The other major approach to improvement in energy density is the use of atmospheric oxygen as the cathodic oxidizing agent. The weight of the cathode in the battery is then limited to that of a catalytically active oxygen electrode, the oxidant (air) being available in limitless amount with no weight penalty.

Power densities are a reflection of the kinetics of the various electrochemical reactions taking place in the battery. They can be improved by attention to certain physical factors, particularly the surface area of the electrode, and are increased at elevated temperatures. For this latter reason, the molten salt systems are particularly favored for applications involving high power density.

This subsection reviews the status of the work presently under way on improved battery systems for use in electric vehicles.

1. High-Temperature Alkali Metal Batteries

a. Lithium-Chlorine

The battery with the highest potential energy density of those now under investigation is based on lithium and chlorine as reactants and is being developed by the General Motors Corporation. Its theoretical energy density is approximately 1000 w-hr/lb. and it has an open circuit potential of 3.5 volts. In its work to date, GM has demonstrated the cell's capability for generating very high current densities – on the order of several thousand amperes per square foot.

The principal liabilities of the lithium-chlorine battery are the difficulties associated with storing chlorine gas under pressure and at temperatures of around 650°C, and the tendency of the cell to self-discharge. The first problem is being tackled by using highly adsorbent charcoal to reduce the pressure of the stored chlorine. This approach seems quite successful, although a great deal more needs to be learned about the cycling capability of charcoal in this application.

While its electrochemical characteristics are very encouraging, the lithium-chlorine battery presents many novel and extremely challenging problems in materials engineering, and extensive development will clearly be needed before the system can be made practical. The question of hazards arising from the storage of chlorine gas under pressure and at high temperatures seems, at this stage at least, likely to limit the chances of such a battery's being adopted as a power source for vehicles.

It is not possible to make any accurate estimates of the effective energy and power densities, still less the costs, to be expected for the lithium-chlorine battery. Much depends on the complexity of the safety engineering and packaging that would be necessary. It seems likely, however, that the system will easily possess the technical capabilities required to satisfy the most exacting of the electric vehicle's specifications.

With regard to costs, a theoretical minimum quantity of about 25 pounds of lithium would be required for a battery capable of meeting the requirements of the family car. At today's price for lithium, $7/lb, this corresponds to $175. The actual quantity of lithium needed might be half as much again as the 25 pounds, but with anticipated lower production costs of the metal in quantity the resulting materials cost for lithium might not be much more than $100. While this is a significant item, it would not appear to rule out the system from further consideration.

Maintenance of the operating temperature is a problem with all high-temperature battery systems. In a well-insulated system, the self-discharge rate is usually sufficient to maintain temperature. However, good insulation tends to be an embarrassment when the battery is working at high power levels, either on charge or on discharge, since the excessive amount of heat generated causes an undesirable rise in the internal temperature. On the other hand, if the battery is to be shut down for long periods, it seems essential that some kind of built-in combustion heater be included in the system.

b. Sodium-Sulfur

Another approach to the use of alkali metals in high-temperature batteries is being taken by the Ford Motor Company. Ford's cell uses sodium and sulfur as the reactants, and the electrolyte is a special ceramic material permeable only to sodium ions. The properties of the ceramic are critical for the effective functioning of this battery. While the sodium-sulfur battery does not have the theoretical energy density of the lithium-chlorine system (300-600 w-hr/lb, depending on the extent of the reaction, versus more than 1000 w-hr/lb), it does have two major practical advantages. First is the lower temperature of operation, approximately 300°C. At this temperature, sulfur is a liquid, and containment of the cathode materials thus presents far fewer engineering problems than in the lithium-chlorine system. The second advantage is that the battery reactants, sodium and sulfur, are both extremely abundant and very inexpensive; there are thus no immediate and fundamental reasons why the battery might not eventually develop into a low-cost power source for large-scale use.

Since Ford's work is proprietary, relatively little specific information is available. Present efforts are apparently confined to experiments with single cells, the goals being to determine the factors affecting electrical efficiency and cycle life and to find solutions for the various engineering and materials selection problems which are encountered. Since multi-cell work is bound to raise a whole new series of problems concerned with design and with maintenance of the electrical balance of cells in the battery, it is not possible to make an accurate prediction of the time scale for the development of this battery into a practical power source for vehicles.

c. Capacitive Storage

A third approach to high-temperature battery development has been taken by the Standard Oil Company (Ohio). SOHIO's work was originally based on the use of carbon electrodes with very high surface areas to provide capacitive energy storage. All electrolyte-electrode interfaces have double layer capacitances; however, these are in general quite small and do not store significant quantities of energy. In the case of porous carbon electrodes, the internal surface can reach huge values, and the amounts of energy that can be stored capacitively become comparable with those stored in a battery of equivalent weight. Electrolytic condensers with capacities of the order of farads can be set up by immersing porous carbon electrodes in an aqueous electrolyte such as sulfuric acid. A very substantial enhancement in capacity and hence in the capability for energy storage, can, however, be obtained by using a molten salt electrolyte. A further bonus comes from the much higher breakdown voltages of these electrolytes, which permit the cells to be operated at levels of 3 volts or more, compared with a maximum of 1.8 volts or so in aqueous systems. Since the energy storage is proportional to the square of the voltage, this means a substantially greater energy density.

In practice, the SOHIO device, which contains a molten potassium chloride-lithium chloride eutectic as the electrolyte, does not behave as a pure capacitor. It was found preferable to substitute aluminum for carbon at the negative electrode (to reduce self-discharge, due to lithium solubility), and the lithium enters the aluminum interstitially. At the positive electrode it seems likely that the chloride ion is at least partly discharged but is adsorbed very strongly on the carbon and so never appears as a gas. The system may thus be partly a capacitor and partly a special type of lithium-chlorine battery in which the active materials remain within the current collectors. The fall-off in voltage as the cell is discharged is intermediate between those typical of batteries and capacitors.

At its present stage of development the SOHIO device appears to be capable of attaining an energy density of 50 w-hr/lb and a power density of 150 w/lb in its packaged condition. Experimental batteries with 30-kwh storage capacity are now being designed. Thermal insulation is provided by a vacuum container which will maintain operating temperature for 40 hours without auxiliary heat. The self-discharge rate is low, taking approximately 20 days from full charge. While the SOHIO battery seems likely to have inherently lower energy densities than those of other types of high-temperature systems, with improvements in the technology of the carbon cathodes, its energy density might eventually be raised to about 100 w-hr/lb. Estimates of cost are necessarily very tentative because of the novelty of some of the fabrication processes, but it appears that in large-scale production they might approach a level of $1.50/lb. Preliminary indications are that the lifetime will be about three years. With a pilot manufacturing plant going into operation SOHIO's battery seems to be most advanced of the high-temperature systems now under development.

d. Lithium Cells With Tellurium, Selenium, and Other Non-Metals

Other types of high-temperature cells involving lithium anodes and molten nonmetallic elements as the cathodes are under investigation at the Argonne National Laboratory. The electrolyte is a relatively low melting ternary eutectic mixture of lithium fluoride, chloride, and iodide made into a solid paste by the carefully controlled addition of micron sized particles of lithium aluminate. The majority of the work has been focused upon the lithium-tellurium and lithium-selenium couples, the cell reaction resulting in the formation of lithium telluride or selenide, which remains dissolved in the molten cathode. Operating temperatures are necessarily above those of the melting points of the cathode elements and are in the 470-500° C range for lithium-tellurium and 350-400° C for lithium-selenium.

The great virtue of these systems is the extremely high degree of reversibility of the electrode reactions and their capacity for sustaining current densities of approximately 10,000 amperes per square foot. Polarization of the cells is very low and entirely accounted for by internal resistance. The major constructional material is Armco iron and corrosion is apparently no great problem. Projections based upon the behavior of single cells having an electrode area of 10 square centimeters indicate that the packaged energy densities would be 90 w-hr/lb for Li/Te and 120 w-hr/lb for Li/Se. Power densities are very high: 200-500 w/lb for Li/Te and 300-600 w/lb for Li/Se.

Probably the greatest handicap to the development of these cells for vehicle applications is the cost and relative scarcity of the cathodic elements. Because of this some preliminary experiments were carried out in recent months with a lithium-phosphorus cell, but the necessity of working above the melting point of red phosphorus requires operating temperatures above 600°C, and the observed voltage of the cell is only about 1 volt versus 1.75 volts for Li/Te and 2.4 volts for Li/Se. This initial work with phosphorus has therefore been unpromising. The most recent work has been with the lithium-sulphur system and has been very encouraging as far as it has gone. This system appears to have great promise as a vehicular power source.

Sodium cells are not of interest because of the higher melting points of the sodium salt electrolytes and the greater tendency of sodium to dissolve in the electrolyte.

2. Alkali Metal Batteries With Organic Electrolytes

The use of nonreactive organic liquids as electrolytic solvents in alkali metal batteries permits ambient-temperature operation and thus avoids many of the difficulties associated with molten salt and ceramic electrolytes. It has its full share of disadvantages, however, since for a variety of reasons, organic liquids are inferior electrolytic solvents.

A great deal of work has been done over the last five years, much of it supported by NASA, on the selection of cathodes and organic electrolyte combinations for use with lithium anodes in primary batteries. The major problems have been the identification of non-aqueous electrolytic solvents compatible with lithium and having sufficiently high conductivity, and of cathode materials capable of sustaining even very small current densities without extremely high polarization. Some progress has been made, although the best of these systems can support current densities only 5-10% as great as those possible in conventional aqueous batteries.

The development of rechargeable systems is at an even earlier stage. In work carried out some three or four years ago, the Lockheed Aircraft Company demonstrated the rechargeability of a lithium-silver chloride battery having a lithium perchlorate-propylene carbonate electrolyte. The best of these cells showed some 40 or 50 cycles of operation at almost 80% discharge before the capacity fell off significantly. This system was not developed further, because the high equivalent weight of the cathode gave it no substantial advantage in energy density over many aqueous systems. Other attempts at recharging organic electrolyte batteries have encountered severe problems with lithium plating and with the recycling or solubility in the electrolyte of the cathode materials (generally halides or sulfides of transition metals).

More recently, Gulton Industries, Inc. has engaged in the development of a rechargeable lithium-nickel fluoride battery having a potassium hexafluorophosphate-propylene carbonate electrolyte. Claims have been made that this battery system has the potential to attain a packaged energy density of 150 w-hr/lb and a power density of 20-30 w/lb; however, the published technical information* shows that achievements to date fall short of these goals. On repeated cycling a nominally 0.025 amp-hr cell discharged for 8 hours at 20 ma (the current density at the electrodes being 0.1 ma/cm^2) showed a voltage decrease of from 3.0 to 1.4, the value at the midpoint being 1.75 volts. If these conditions are typical, then a 13-amp-hr cell which apparently weighs 0.55 pound would deliver 27 w-hr/lb, or approximately 40 w-hr/lb if the cell were discharged completely. High discharge currents have been reported, but only for pulse conditions of perhaps a few milliseconds. The falloff in voltage at a steady discharge current density of only 0.1 ma/cm^2 indicates that high power densities are unlikely to be attained under sustained conditions. A five-hour discharge rate may well be the practical limit for this type of battery.

Gulton has had more success than other groups in recharging lithium non-aqueous batteries, but even so they have found it necessary to use low current densities and very thin coatings of active material on the current collector to achieve significant cycle life. The latter requirement, of course, tends to decrease the energy density of the cell.

As a class, rechargeable alkali metal batteries with organic electrolytes seem a long way from practicality for vehicle use. Their difficulties derive from fundamental electrochemical problems which even in comparison with the engineering problems faced by the high-temperature batteries, could take a long time to resolve. Gulton Industries, however, is optimistic about their prospects and has entered into a vehicle development program with American Motors Corporation (see Appendix A) to use its battery with a high-rate nickel-cadmium battery in the hybrid power source described in Section V-D. The long-term cost estimates for the lithium battery have been estimated to be in the range of $4 - 5/lb.

The Electrochimica Corporation has also advocated the use of organic electrolyte lithium batteries in electric vehicles. Its work has been concentrated on a lithium-copper fluoride system, and claims are made that this system has particularly high current densities for this class of battery. Lacking specific information, we cannot make a detailed assessment of the system. It is not claimed to be rechargeable, however, and therefore is not yet at a stage for consideration in vehicles.

3. Metal-Air Batteries

The employment of air cathodes represents another general approach to the development of batteries with higher energy density. In most programs in this area, aqueous electrolytes have been used in combination with relatively conventional metal anode materials. The concept is not new; low-rate zinc-air primary batteries have been available for more than half a century. The novelty in the recent work is in the use of air cathodes capable of supporting very much higher current densities than those of the conventional cells, an advance derived from fuel cell technology.

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* H. N. Seiger, S. Charlip, A. E. Lyall, and R. C. Shair, *Organic Electrolyte Batteries*, paper presented at 21st Annual Power Sources Conference, Atlantic City, N. J., May 16-18, 1967.

The electric vehicle application requires rechargeable batteries, which present additional problems to air-cell technology. Problems arise with the rechargeability of the anode and with the oxidation resistance of the air cathode, which has to withstand oxygen evolution or be supported by an auxiliary third electrode for recharging. The work on zinc-air cells is hampered by the classic difficulties of recharging the zinc electrode, of which dendrite growth is the most significant. The following paragraphs review the present activities in metal-air battery development.

a. Zinc-Air (General Atomic)

One of the most prominent of the programs on zinc-air batteries is that being conducted at General Atomic, now a division of the Gulf Oil Corporation. The work is supported in part by the Edison Electric Institute, and the British company, Joseph Lucas Ltd., has become a partner in the program. The basic approach taken is to avoid the dendrite growth problem by pumping the electrolyte over the surface of the electrode. The technique is very effective but results in considerable engineering complexity. On discharge, the reaction product, zinc oxide, is swept out of the cell and stored separately, being fed back in again on charge. The cathode is of sintered nickel with a palladium catalyst, and air is forced through it with a compressor. The system appears to have a near-term energy density capability of 50-60 w-hr/lb and a power density capability of 30-35 w/lb. These figures are net after subtracting the parasitic power load for pumps, compressors, and other auxiliary equipment. This latter drain is estimated at a fairly constant 15% of gross power output in the size range of greatest interest, 20-80 kw.

The largest modules built to date have been sized at 15 kwh, 4-5 kw at 36 volts, and they will be used to determine the performance of the system on extended cycling. A full charge can be completed in about two hours. If the system is not abused electrically, it would appear to have a cycle life comparable to that of the lead-acid battery. Carbon dioxide contamination of the electrolyte is a problem but may be dealt with by changing the electrolyte occasionally, perhaps with the same frequency as oil is now changed in a gasoline engine.

Realistic estimates place the cost of the General Atomic battery in the range from about $1.50/lb for one designed with good energy storage but only limited power capability to about $3.30/lb for one with the highest power density of which the system is capable. At present, the major objective of General Atomic's project is the electric lift truck application.

b. Zinc-Air (Leesona)

The Leesona Corporation is also very active in metal-air battery development. While much of its effort is in the primary zinc-air field, it is also investigating electrically rechargeable secondary battery systems. It has developed a mechanically rechargeable zinc-air battery, which is now being delivered to the Army and Marine Corps. The latter battery, which is designed as a power source for military communication systems, is far too costly to consider as a vehicular power source. Even if anode costs were simply those of the materials, with a credit for the discharged anode, mechanically rechargeable systems would still appear to be several times too expensive for consideration in vehicles.

The work on secondary zinc-air batteries at Leesona is based on configurations which are similar to those of the company's primary metal-air batteries. Much of its effort is directed at improving separators, both organic and inorganic; Leesona is a licensee of the inorganic separator developed by the Astropower Laboratory of McDonnell-Douglas, Inc. (see below). Leesona is also investigating the effect of close control of charging current density and pulse charging in attempts to solve the problem of dendrite growth.

The Leesona primary zinc-air battery delivers as much as 116 w-hr/lb in radio service and can sustain steady discharge at a power density of 18 w/lb. Such favorable parameters are unlikely to carry over to electrically rechargeable secondary systems, where good cycle life is possible only when the battery is not completely discharged.

The future costs of Leesona's electrically rechargeable zinc-air battery, manufactured in quantity, can only be guessed, because so much depends on the quantities and costs of catalysts required for the cathode and the degree of complexity in the battery structure; a figure of $1.50-$2.00/lb might be reasonable. It is generally agreed that the technical problems associated with such cells are far from being solved and their introduction lies in the indefinite future.

c. Sodium-Air

An interesting variant on metal-air batteries – one which permits the use of an alkali metal anode – is the sodium-air battery being developed by the Atomics International Division of North American Rockwell Corporation. Each cell of this battery is essentially two cells: one is a sodium-sodium amalgam cell with a molten salt electrolyte, and the other is formed by the sodium amalgam with an air cathode in an aqueous sodium hydroxide electrolyte. The system is made feasible by the development of a very low-melting eutectic sodium salt mixture as the electrolyte for the sodium-sodium amalgam cell, in which the sodium ion is the sole current-carrying species. Because of the low melting point the temperature of operation is not much above 100°C, which is quite compatible with the operation of the sodium amalgam-air cell.

The sodium-air battery is still at an early stage of development. Experience with it is limited to prototype models which generate about 25 watts and which have completed about 50 operating cycles. The air cathode, which has not been optimized, is a modified form of an American Cyanamid electrode containing about 10 milligrams of platinum per square inch. The relatively low temperature of operation permits the use of plastics, particularly polypropylene, as materials of construction. The molten salt electrolyte is contained in a porous alumina disc in some designs and is unconstrained in others.

Projections based on extrapolations from early results indicate that energy densities for a 20-kw battery would be in the range of 100-150 w-hr/lb and power densities would be 25-35 w/lb, with ultimate capabilities significantly higher than these figures. The power densities are, however, based on current densities that may necessitate uneconomically large quantities of platinum in the air cathodes.

In addition to the platinum, mercury is also a major material cost. Overall manufacturing costs for the battery on a large scale are estimated at being in the \$1.50 to \$2.00/lb range, which is similar to those projected for many of the high-temperature batteries. The cost related to the engineering complexity of the sodium-air cell is offset by the use of economical plastic materials in its construction.

From the operational standpoint the sodium-air concept has a number of attractive features for possible application as a vehicle power source. It has a much lower temperature of operation than the other alkali metal-molten salt systems, and its power density is likely to be higher than those of the organic electrolyte batteries. Moreover,it retains the molten anode feature and thus avoids the difficulties of dendrite formation on recharge. A further consequence of the molten and thus structureless anode is that mechanical rechargeability is more likely to be economically feasible than with other types of metal-air battery.

On the negative side, the cell appears to be rather complex,and operating experience with it is limited. The long-term stability of the low-melting eutectic mixture may be a questionable feature, but the self discharge rate at the sodium amalgam-sodium hydroxide interface is apparently low.

Atomics International has recently formulated a design in which the two cells of the battery are constructed as separate entities and the sodium amalgam is pumped between them. While this would require somewhat greater quantities of mercury, cell construction would be simplified, reliability would be enhanced, and it is predicted that overall costs would be reduced.

d. Other Metal-Air Batteries

In addition to the work reviewed above,there is a great deal of other activity in the field of rechargeable metal-air batteries. On the basis of the little information that has been published, none of it appears to be at a more advanced stage than the programs already described. Union Carbide and ESB, Inc. are working on electrically rechargeable zinc-air systems generally similar to that of Leesona. Yardney Electric Corporation, in a program partly sponsored by the Ford Motor Company, is developing its "Rotoxel" zinc-air cell in which dendrite formation at the zinc anode is prevented by rotating the zinc anode against a doctor blade; this cell uses silver catalysts at its air cathode. The Astropower Laboratory of McDonnell-Douglas Corporation is also investigating rechargeable zinc-air cells, making use of its novel inorganic separator developed originally for heat sterilizable silver-zinc batteries; this separator is reported to achieve a significant reduction of dendrite growth on zinc during recharge.

Globe-Union, Inc., in a program sponsored by the U.S. Army Electronics Command, is investigating a lithium-moist air battery in nonaqueous solvents. While this might represent the ultimate in theoretical energy density for metal-air cells, the practical difficulties appear to be overwhelming.

General Telephone and Electronics has a program on the iron-air battery. In view of the maturity of the technology of rechargeable iron electrodes, this might be a promising approach.

Zaromb Research Corporation is investigating aluminum-air cells, but in spite of their attractive theoretical energy densities, they are relatively unpromising. Less than half the theoretical voltage is obtained, leaving the rest to appear as heat. As the aluminum electrode cannot be recharged electrically, the system can be considered potentially rechargeable only on a mechanical basis. The General Electric Company has developed a mechanically rechargeable magnesium-air battery conceptually similar to the Leesona zinc-air system but has not advanced it as a possible vehicle power source. General Electric is also investigating rechargeable cadmium-air systems, as is Union Carbide. These latter systems, however, are not being considered as potential power sources for vehicles.

4. Nickel-Zinc

While the high level of present interest in this system is not directly related to electric vehicle development, the nickel-zinc battery has, potentially at least, performance parameters which merit consideration for vehicle applications. The substitution of zinc for cadmium should give it approximately double the energy density of the nickel-cadmium system (i.e., about 30 w-hr/lb), and the power density should be comparably high. There is no problem of material availability with zinc; the costs of the battery should be appreciably less than those of nickel-cadmium batteries, although as a nickel-alkaline system it is still likely to be expensive compared with lead-acid.

The major difficulty with the nickel-zinc system is the classic problem of obtaining an adequate cycle life from any rechargeable battery containing a zinc anode. General Telephone and Electronics, which is one of the companies investigating nickel-zinc cells, has reported cycle lives of 100-200 but at only 50% discharge, which nullifies its advantage over nickel-cadmium in energy density. General Electric has reported improved cycle life by incorporating calcium hydroxide in the electrolyte to limit the concentration of soluble zincate, but this too lowers the energy density. Also active in the field are Texas Instruments, Eagle Picher, Yardney Electric, and others.

Even if perfected, the nickel-zinc battery would still seem to be too costly as the prime power source for an electric vehicle, but it might have some promise in hybrid mechanical-electrical systems (see Section VI). Until a reasonable lifetime has been demonstrated, however, its prospects as a vehicle power source remain speculative.

C. FUEL CELLS

Fuel cells are essentially steady-state primary batteries and are of interest for electric vehicle applications mainly because vehicles so powered would have no requirement for electrical recharging. They would thus be no more restricted in range than are conventionally powered vehicles. Because of this, energy density is not a meaningful parameter for fuel cells; an evaluation of their applicability to vehicles turns upon their power density, reliability, and potential cost.

Fuel cells, which exist in a wide variety of types, can be differentiated by the nature of the fuel used – hydrogen; water-soluble substances such as hydrazine, methanol and ammonia; hydrocarbons – and by their temperature of operation: ambient, moderately elevated (80-150°C), or high (500-1000°C). Since hydrogen reacts so easily in a fuel cell but is an inconvenient fuel to handle, several types of fuel cells convert other fuels into hydrogen as the first step. These are called indirect fuel cells. The types of greatest interest for vehicle application are ambient-temperature hydrogen systems, both direct and indirect, and soluble fuel systems. On a conceptual basis the U.S. Army has also considered a high-temperature fuel cell-battery hybrid system involving a high-temperature hydrocarbon fuel cell.

1. Ambient-Temperature Hydrogen Systems

Ambient-temperature hydrogen fuel cells have reached a relatively high degree of reliability, and several thousand hours of trouble-free operation are now commonplace. The major limitations of these systems for application in electric vehicles are their relatively low power density and their high estimated production costs. As a general rule, restrictions on current densities imposed by problems of heat dissipation and electrode polarization limit power densities to levels of around 30 w/lb or so. More serious is the cost restriction, which has two major causes: 1) precious metal catalysts are necessary to generate acceptable current densities and 2) the problems controlling materials transfer across the boundaries of fuel cells make the engineering problems of the latter more complex than those of batteries.

The present state of the art in ambient-temperature hydrogen-air fuel cells is such that cells can be operated with no precious metal catalyst at all, but the current densities would be too low for vehicle applications. A loading of about 5 milligrams of platinum per square centimeter of electrode presently appears necessary to give a power density of 25 w/lb to a hydrogen-air fuel cell and this may be improved to 50 w/lb in ten years.* Present costs of such cells are no reliable index of future costs, since they are all essentially handmade. The most optimistic estimates for future volume production are in the range of

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* *The Automobile and Air Pollution: A Program for Progress*, Report to the Panel on Electrically Powered Vehicles (R. S. Morse, Chairman), U. S. Department of Commerce, October 1967.

$100-$150 per kw. To this must be added the cost of the fuel supply system. Cylinder hydrogen is probably impractical due to its bulk and weight; liquid hydrogen is a distinct possibility but will certainly add significant costs for cryogenic storage. Indirect fuel cells would require equipment to reform hydrocarbons or methanol or to crack ammonia. None of these possibilities appears likely to involve the addition of less than $50/kw to the first cost; and thus, $150-$200/kw seems to be a limiting cost range for such systems.

Operational costs are likely to be quite moderate if hydrocarbons or methanol are used as fuel, since the conversion efficiency of the fuel cell is much higher than that of the internal combustion engine. The extent to which there would be a road tax on fuel-cell-powered vehicles is a major unknown factor here. In addition, fuel cells with alkaline electrolytes would need occasional changes of electrolyte because of gradual contamination with atmospheric carbon dioxide.

2. Soluble Fuel Systems

Soluble fuel types will in general involve even higher first costs than will hydrogen fuel cells. Those using ammonia or methanol call for much higher loadings of platinum catalysts per unit area, and their power density is not as great. Relatively low costs would be associated with a hydrazine-fed fuel cell, but this material is presently too costly (hydrazine hydrate costs approximately $1.00/lb) and there seems little prospect for a great enough cost reduction to make it a practical fuel.

3. Direct Hydrocarbon Fuel Cells

Research activity continues with direct hydrocarbon fuel cells, using aqueous electrolytes, particularly phosphoric acid, at temperatures of about 150°C. While the reactivity of the hydrocarbons is higher than was earlier thought possible, the quantities of precious metal catalyst required are still, and are likely to remain, orders of magnitude higher than those which could be contemplated in an electric vehicle.

4. Platinum Availability

The use of platinum in fuel cells is potentially restricted not only by cost but also by availability On the basis of today's technology, a full sized car powered by a fuel cell might have a platinum requirement in the range of 1 to 10 pounds. This should be compared with an annual world production of this element of about 60,000 pounds and an estimated reserve of 10 million pounds. Clearly, the world's present apparent resources of platinum are not sufficient to support the widespread use of fuel cells in vehicles. Considerable research effort is being expended in a search for alternative and noncritical catalyst materials, but the results to date are not particularly promising.

High-temperature fuel cells capable of utilizing hydrocarbons directly do not use precious metal catalysts and hold promise of a lower ultimate cost structure than those for other types of fuel cells. They are, unfortunately, excessively heavy, and the problems of reliability and control are exacerbated by the elevated temperatures.

5. Overload Capability

A consideration of the fuel cell's prospects solely in terms of cost per kilowatt may lead to an excessively pessimistic outlook, since some allowance should be made for its overload capabilities. Power rating is a term calling for close definition; if the demand for maximum power is infrequent, a much lower rating is possible for the fuel cell than would be possible with a battery power source. For example, Union Carbide's hydrogen-oxygen fuel cell for the GM Electrovan* had a rating of 32 kw but a maximum output of 160 kw. The exact degree and duration of overload possible with a given fuel cell system will vary with its individual peculiarities, but it seems reasonable to take a factor of three as being representative. In such a case the family car of Table 1 might be adequately powered by a 30-kw cell rather than one of 90 kw. Even so, at an estimated $200/kw, the fuel cell would be prohibitively costly.

6. Present Applications

While much effort is being expended in the United States and elsewhere on fuel cell development, relatively little is focused on highway vehicle applications, most probably for the reasons of cost. Major engineering programs at General Electric, Pratt & Whitney Division of United Aircraft, Allis Chalmers, Union Carbide, Texas Instruments, and Monsanto have been concerned more with the fuel cell's application as a power source for space satellites, both manned and unmanned, as a means of generating electricity from natural gas in the home (a program at Pratt & Whitney in which the Institute of Gas Technology also participates), as a power source for the military in the field, and as a power source for industrial vehicles, particularly fork lift trucks. Overseas, ASEA in Sweden has built fuel cells for submarine propulsion. (This and other European activities are reviewed in Appendix B.)

Direct application of the fuel cell to highway vehicle propulsion has been confined to two experimental vehicles: the GM Electrovan, powered by a Union Carbide hydrogen-oxygen cell, and an M-37 truck modified by the U.S. Army Engineers R&D Laboratory to use a Monsanto hydrazine-air cell. Some notes on these two vehicles are contained in Appendix A. In Europe the French Government is sponsoring an electric car program based upon a 25-kw hydrogen-oxygen fuel cell system (see Appendix B).

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* See Appendix A.

D. ELECTROCHEMICAL HYBRIDS

Many of the electrochemical power sources reviewed in this section have had certain favorable properties for the electric vehicle application, but some of their other properties might be unacceptable. The most common situation, exemplified by fuel cells and alkali metal-organic electrolyte batteries, is good energy density allied with inadequate power density. One solution to this difficulty is to use a combination or hybrid power source in which each component provides properties which complement those of the other. Thus, a low-energy-density, high-power-density battery such as nickel-cadmium can be combined with a high-energy, low-power battery or fuel cell.

There are a number of fairly apparent drawbacks to electrochemical hybrid systems. First, they are more complex than a single power source and thus require significantly more complicated control equipment. Second, the energy efficiency of the hybrid tends to be low because of the losses involved in the internal redistribution of charge among the components of the power source. A further difficulty is that, future high-temperature systems aside, the most suitable battery for the hybrid systems is nickel-cadmium which has the limitations of high cost and materials availability problems, previously noted. As mentioned elsewhere in Sections VI and VII, the development of high-power-density "pile-type" lead-acid batteries would improve the prospects of hybrid power sources.

In spite of these difficulties, electrochemical hybrid systems offer enough advantages to have been the subject of a number of detailed paper studies and the power source for at least one experimental vehicle. There are two subcategories – fuel cell-battery hybrids and battery-battery hybrids.

1. Fuel Cell-Battery Hybrids

Fuel cell-battery hybrids offer possibilities for improving the prospects of the fuel cell as a vehicle power source on two counts. The battery can be chosen to give the overall system an adequate power density and, since its specific costs are likely to be lower than those of the fuel cell, the overall cost per kilowatt will be lessened. The system retains the fuel cell's advantages of rapid refueling and a range limited only by the size of the fuel tank.

Union Carbide Corporation, which built the hydrogen-oxygen fuel cell for the GM Electrovan,* has carried out a conceptual study of coupling a fuel cell with nickel-cadmium batteries for the same application. It concluded that the same performance could be obtained by reducing the fuel cell stack weight from 1345 to 690 pounds and incorporating 427 pounds of nickel-cadmium batteries. Further weight savings would be effected in other parts of the system. The study was not intended to find the optimum makeup of the system but was merely a first approach based on the present state of the art. The battery would be capable of putting out 128 kw of power for short periods; based on a rule of thumb of $3/lb for nickel-cadmium battery costs, it would give peak power capability for about $10 per kw, considerably less than could ever be expected from a fuel cell.

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* See Appendix A.

Union Carbide has also constructed for demonstration purposes a small electric motorcycle powered by a hybrid combination of hydrazine-air fuel cell and nickel-cadmium batteries. The power rating of the fuel cell in the system was 0.8 kw.

Another approach to fuel cell-battery hybrid power sources is being studied at the U.S. Army Engineers R&D Laboratories at Fort Belvoir. This concept would combine a high-temperature hydrocarbon-air fuel cell of the type being developed at Texas Instruments, Inc., with a high-temperature alkali-metal battery (for which the SOHIO system is a likely candidate). The advantages include the ability to use conventional fuels directly, a high power density due to the properties of the battery, and the possibility of using waste heat from the fuel cell to maintain the temperature of the system, thus eliminating the need for a separate heater.

The high-temperature fuel cell-battery hybrid has certain logistic attractions for the military because it is designed to operate on standard hydrocarbon fuels, but it seems a rather remote possibility for general application. If the technical problems of their development can be solved adequately, high temperature batteries are likely to be the sole power source in a vehicle. The fuel cell would add increased range capabilities but at a higher first cost and much greater complexity.

2. Battery-Battery Hybrids

The most prominent example of the battery-battery hybrid is a system proposed by Gulton Industries, Inc., presumably to be the power source for the experimental vehicle being developed in Gulton's joint program with American Motors Corporation. It will consist of a high-energy-density lithium-nickel fluoride battery (see Section V-B-2) in combination with a high-power-density "bipolar" nickel-cadmium battery. The latter has a pile-type construction and has been developed by Gulton specifically for applications involving high discharge rates. The hybrid system is expected to combine the best features of both batteries.

The General Electric Company has used a hybrid battery system in its small experimental electric vehicle (see Appendix A). The major energy source is a lead-acid battery; to enhance the vehicle's acceleration, a small nickel-cadmium battery having about 5% of the capacity of the lead-acid battery is connected in parallel with it. The system apparently operates successfully, and the vehicle has significantly better performance than it would have with lead-acid batteries alone.

VI. MECHANICAL-ELECTRICAL HYBRIDS

The power source for an electric vehicle can, of course, be an electrical generator activated by some kind of combustion engine. This is the basic system used in diesel-electric locomotives and, to a limited extent, in large diesel-powered off-highway vehicles for heavy construction work. Combustion engines are inevitably a source of some pollution, but it is reasonable to expect that the pollution could be minimized if they were specially designed to operate at a constant power output, as would be possible in a hybrid system. The fluctuating power demand would be met by a battery connected in parallel with the generator. The system might take any one of the four forms shown in Figure 10.

Hybrid systems can, in principle, have any desired ratio of engine-generator to battery power. In practice, however, it would seem desirable to have the engine-generator capable of supplying the average power level used by the vehicle plus sufficient reserve to ensure that the battery never became fully discharged in normal driving situations. This would make the hybrid vehicle independent of battery charging facilities and would eliminate from consideration engines which are uneconomically small,* since the power/cost ratio of engines decreases significantly as the size falls to a few kilowatts.

An engine much larger than the average power rating is undesirable, however, since if it were being run at constant power, much energy would be wasted in overcharging the battery. Shutting off the engine when the battery is fully charged is not a solution to this difficulty, because the vehicle could not then respond rapidly to a demand for power greater than could be supplied by the battery alone.

The driving cycle used in the calculations of vehicle performance parameters (Table 2) indicates that the average power demand in the moving vehicle is about 24% of the peak demand. This may be somewhat on the low side for vehicle performance as a whole, since the cycle is concerned with city driving conditions. We have therefore arbitrarily chosen to consider the prospects for mechanical-electrical hybrids on the basis of the engine's having a continuous power output equal to 40% of the peak power demand. This would provide a good reserve for unusually prolonged operation at high power demand and also permit the use of power-consuming auxiliaries such as air conditioning.

Of the four possible systems shown in Figure 10 we consider the ac generator-dc motor combination (d) the most immediately promising. The ac generator is attractive because it has no brush maintenance and replacement problems, and because it can run at high speeds and is thus very compact. Moreover, the technology of mass producing such

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* The few hybrid vehicles in commercial production for use on the highway utilize a relatively small engine-generator system manufactured by G&M Power Plant Co. Ltd., of Ipswich, England. Designed for attachment to electric milk trucks and similar vehicles, the engine-generator serves merely to extend the range of what are essentially battery-powered vehicles.

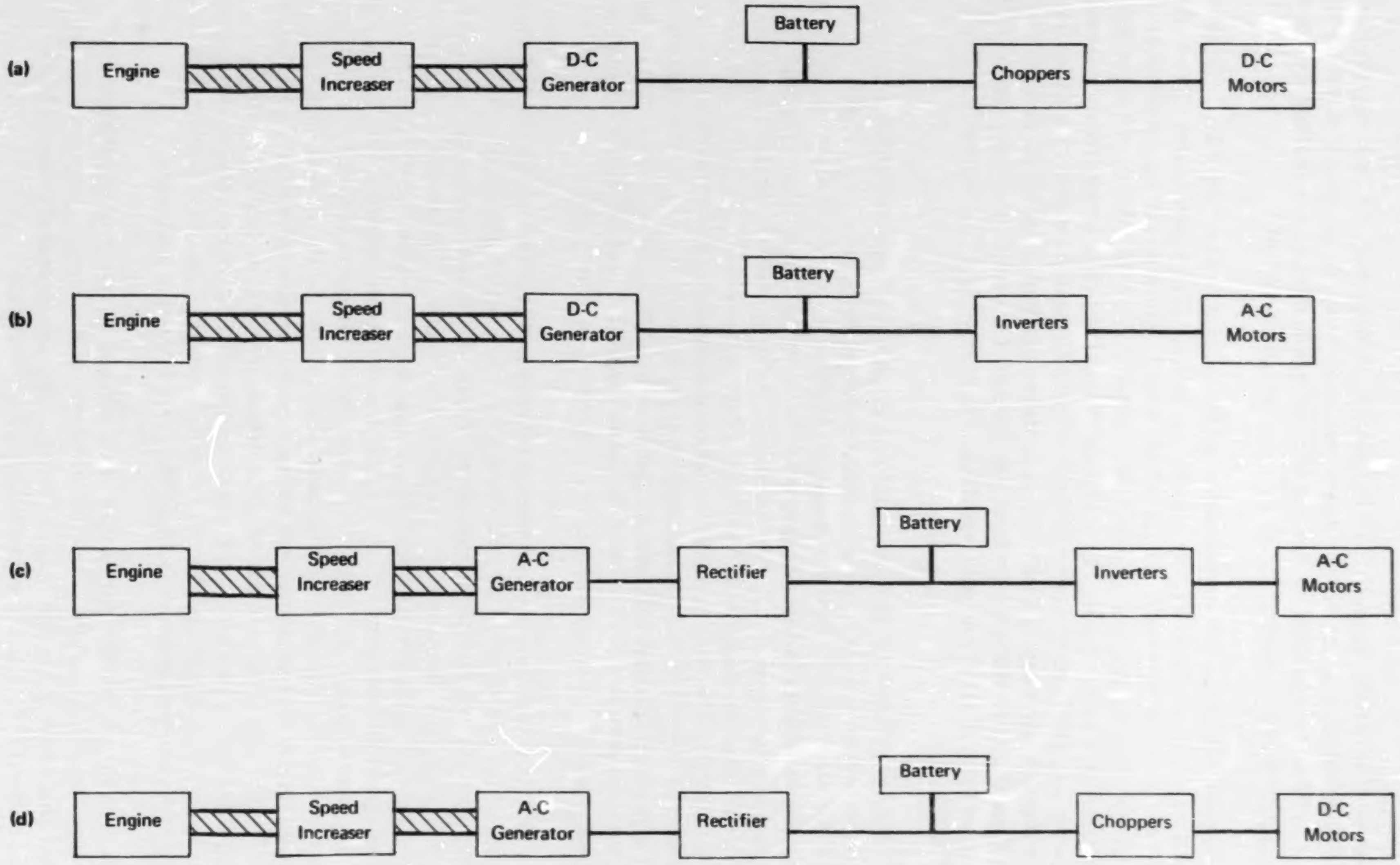
(a)
Engine
Speed Increaser
D-C Generator
Battery
Choppers
D-C Motors
(b)
Engine
Speed Increaser
D-C Generator
Battery
Inverters
A-C Motors
(c)
Engine
Speed Increaser
A-C Generator
Rectifier
Battery
Inverters
A-C Motors
(d)
Engine
Speed Increaser
A-C Generator
Rectifier
Battery
Choppers
D-C Motors

FIGURE 10 VARIOUS ELECTRICAL SYSTEMS FOR ELECTRICAL-MECHANICAL HYBRIDS

generators is well advanced because of the general introduction of the alternator in conventionally powered vehicles some five or six years ago. A dc motor is preferred, however, for traction; as explained in Section IV, the principal reason is the high cost and weight of the inverter system needed by an ac motor for speed control.

To evaluate the technical requirements of the hybrid system, we follow the same general procedure as that used for the purely electrochemical power source. From the weight available for the power sources (line 17 of Table 1), we subtract the weight of an ac generator, rectifier, speed increaser, and voltage regulator rated at 40% of the final peak power requirement for each vehicle. The remaining weight can then be distributed between the prime mover and the battery. Our approach has been to estimate weights for the former based upon existing technology and then calculate the power density which is required from the battery. Provided it is sufficient to meet the demand for maximum power, the energy density of the battery is of secondary importance, since the source of energy is the fuel fed to the prime mover.

Five different classes of engines could conceivably be employed in a mechanical-electrical hybrid system. Three of these – the gas piston engine, the diesel piston engine, and the gas turbine engine – involve internal combustion; the others – the Rankine cycle (steam) engine and the Stirling engine – involve external combustion. The latter two can be operated at lower overall pollution levels than the former, since external combustion can be carried out in a comparative excess of air (although oxide of nitrogen production is enhanced); nevertheless, the data available on steam engines and Stirling engines in the size range of interest (reviewed in the recent report* by the Battelle Memorial Institute) are so meager that a separate analysis of their prospects in hybrids is not justified. Since their power/weight ratio appears to fall within the same range as the diesel piston engine, the calculations for this engine can be used as a first approximation for them.

Representative data for the technical performance of gas piston engines and diesel piston engines in the size range of interest (6-60 kw) are plentiful, and some data exist for the gas turbine at the upper end of this range. Figure 11 shows some estimates of the weight-to-power ratio for these types of engines, and Figure 12 shows estimates of the corresponding factory costs per kilowatt. These data are for engines with anticipated life times of 2500 operating hours, manufactured in quantities greater than a hundred thousand units annually and designed for constant power service at their rated load in a hybrid vehicle. Their parameters therefore correspond more closely to the engine technology of long-haul truck service and industrial applications, where average operation is close to the rated power level, rather than to that of conventional automobile engines, whose average operation calls for only 20-25% of the maximum rated power. For gasoline and diesel engines, which are very mature products, the power rating is the main influence on the power/weight ratio, and production volume is the main determinant of costs.

The technology of gas turbines is well advanced, but the translation of this technology into economic solutions to the problem of automotive propulsion is in its infancy. Few units exist in the size range of interest, and the estimated values in Figures 11 and 12, particularly of cost, must be regarded as very approximate.

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* Battelle Memorial Institute, "Study of Unconventional Thermal, Mechanical, and Nuclear Low-Pollution-Potential Power Sources for Urban Vehicles," by J. A. Hoess, *et al.*, Summary Report to U. S. Dept. of Health, Education and Welfare, March 15, 1968.

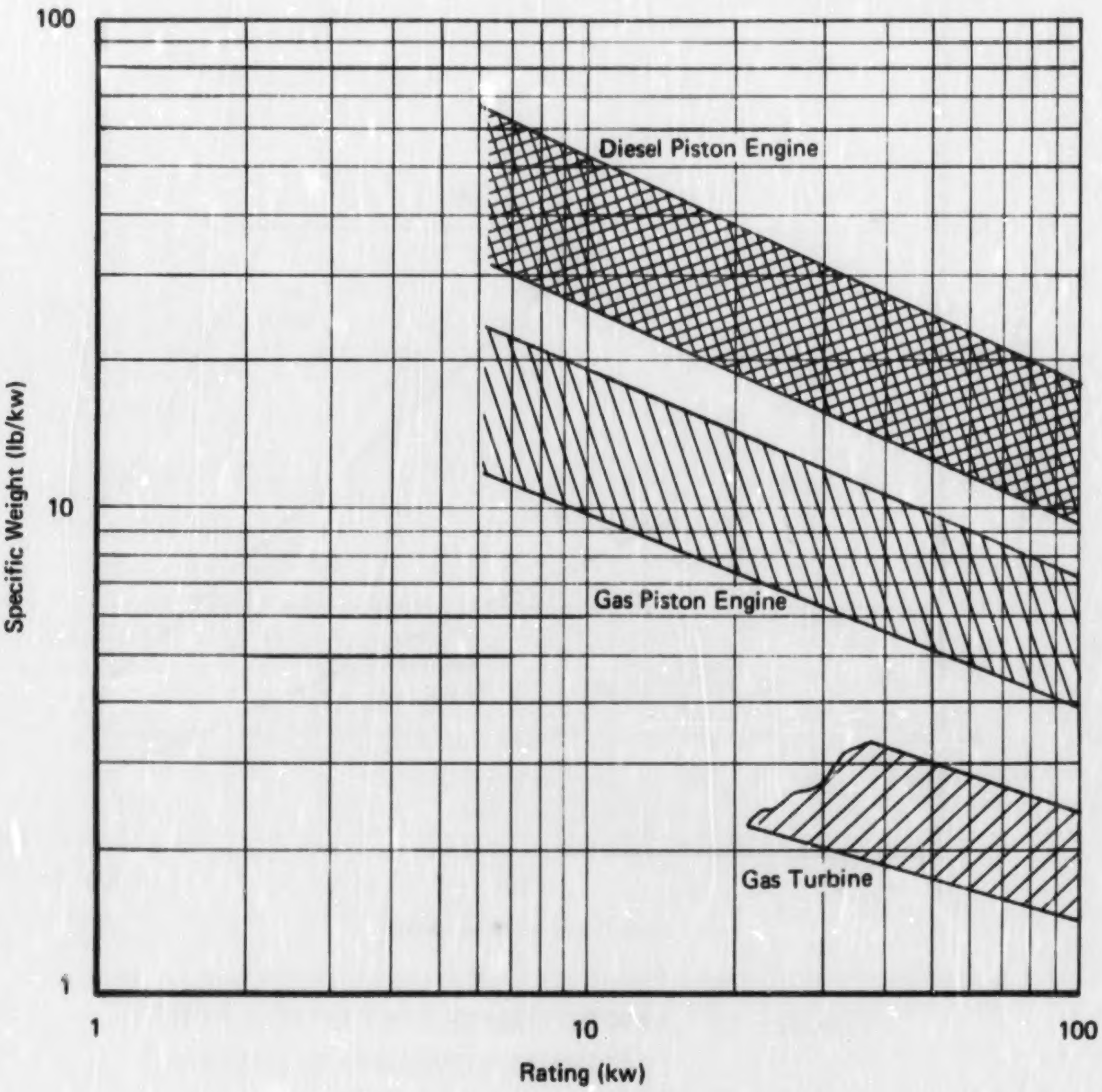

FIGURE 11 POWER/WEIGHT RATIOS FOR INTERNAL COMBUSTION ENGINES

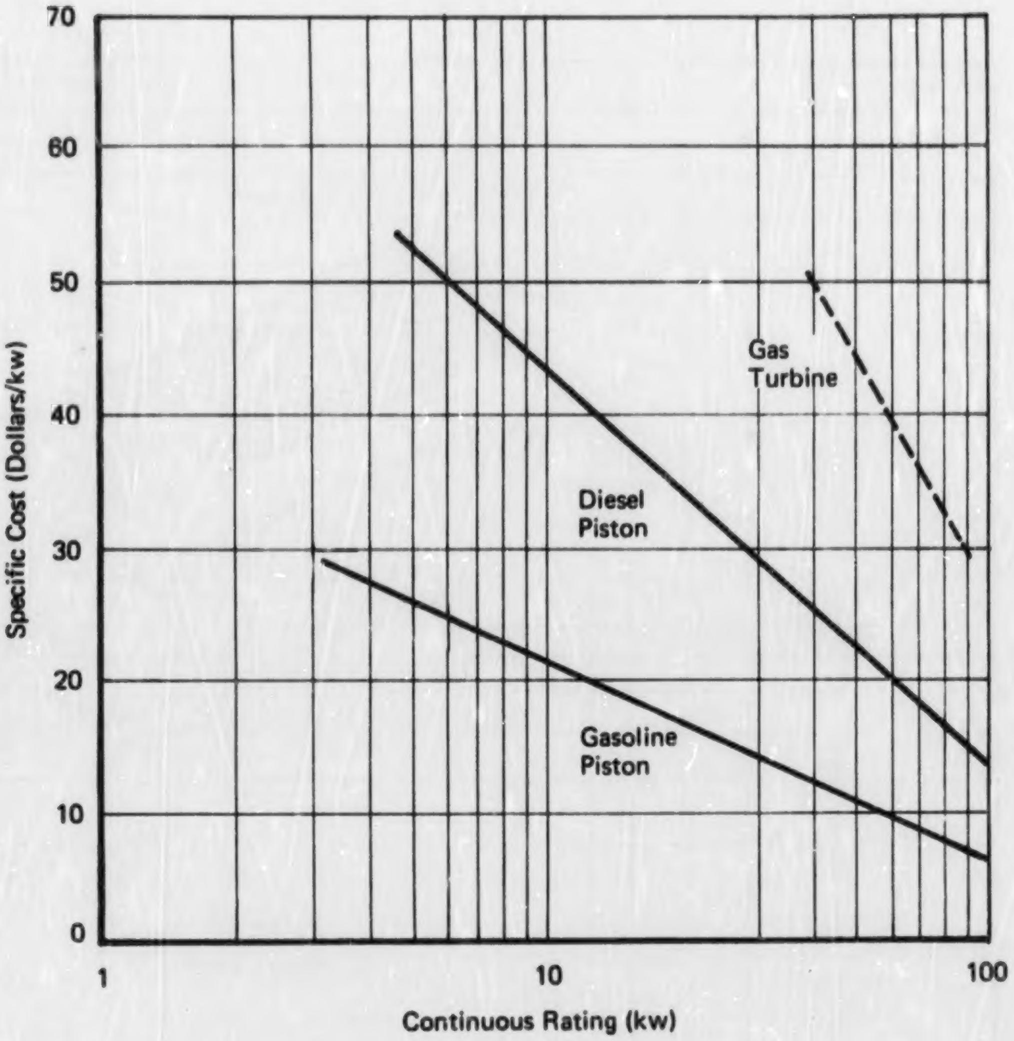

FIGURE 12 APPROXIMATE COST LEVELS FOR INTERNAL COMBUSTION ENGINES

The weight estimates for the ac generator are taken from Figure 13. These correspond to machines running at speeds of 12,000 rpm in the higher end of the power range and as high as 16,000 rpm in the lower end. They are representative of the technology used in equipment which is already in existence, particularly for aircraft applications, and which might be manufactured at low unit cost if sufficient demand developed. (Figure 13 also makes allowance for the relatively small extra weight associated with the rectifier and the speed which the system requires.)

Using the data from Figures 11 and 13, the weights of generator and engine rated at 40% of the peak power requirement have been calculated for each of the six classes of vehicle and for each of the three engine types. The permissible weight for the battery and thus its required power density are derived from these calculations and are presented in Table 5. The first two lines of the table are, respectively, lines 12 and 17 of Table 1.

The results of the calculations, which at first sight are somewhat surprising, indicate that the power density requirements for the batteries in hybrid vehicles are only slightly lower than for those in vehicles powered solely by batteries. These requirements are not particularly sensitive to the arbitrary choice of a 40/60 prime-mover-to-battery ratio. Thus, among vehicles with gasoline engines and with conventional construction the family car shows essentially no change, while in the most favorable case, the city bus, the reduction is above 30%, from 36 w/lb to 25 w/lb. In the case of the diesel engine, the power density requirement for many hybrid vehicles is actually greater than when the battery is the sole power source; this results from the relatively high weight which must be assigned to the diesel engine.

Although the engines which would be used in the hybrid are smaller than those used in corresponding conventionally powered vehicles, the weight differences are not great. The larger maximum power capability of conventional vehicles does not call for substantially greater weight, because the engine is not built to run steadily at the higher power level. Also, the power density of internal combustion engines decreases as the size falls, so a small decrease in average power level does not return a proportional decrease in weight. The decrease in battery power density requirement for the hybrid involving a gas turbine engine is somewhat greater than for the two piston engines, but unfortunately the technology of small gas turbines is not well established, and their cost, which might be in the range of \$40-\$100 per kilowatt in the size range of interest, is likely to be discouragingly high.

The major differences between the battery requirements in the pure electric and the hybrid is that, in the latter, 1) energy density is of small importance and 2) the maximum power density is reduced by about one-fifth. The power density requirements for the family car, however, still restrict the choice of batteries primarily to the high-temperature alkali metal type (among which the SOHIO system's high power density capability might be particularly attractive); the sole exception to this statement is the nickel-cadmium battery, which has excellent power characteristics but low energy density.

For vehicles other than the family car, the power density requirements of the hybrid could be satisfied by metal-air battery systems; for various technical reasons, however (such as corrosion at the air cathode), this class of battery does not appear to be suitable for the

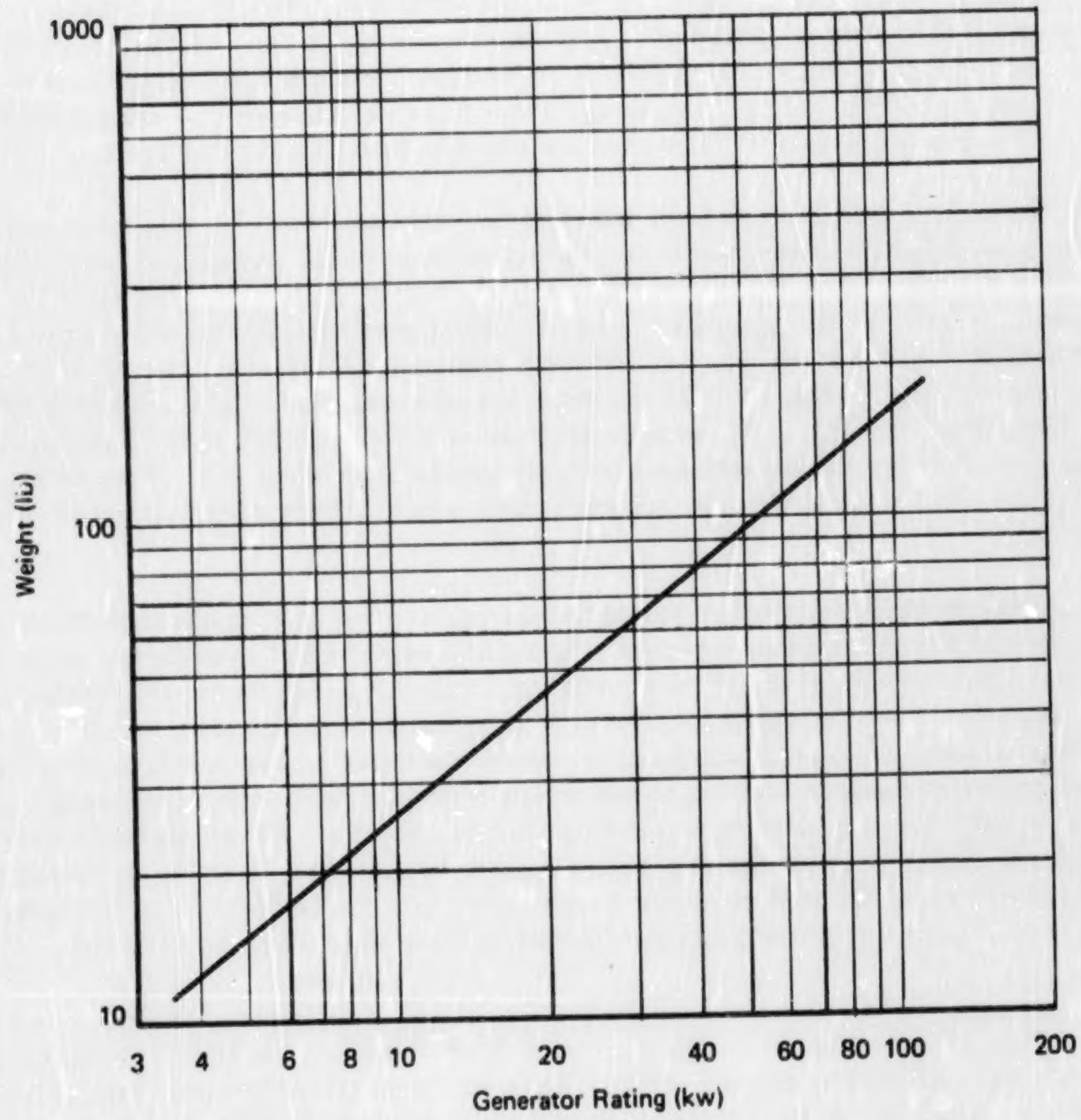

FIGURE 13 WEIGHT OF GENERATOR, RECTIFIER, SPEED INCREASER AND VOLTAGE REGULATOR

"float charge" service characteristic of the hybrid application. More important is the possibility that the lead-acid battery might qualify for the non-family-car hybrid applications. The power requirements are somewhat high for it, except for the city bus, but its power density might be increased with further development of pile-type construction.

From a cost standpoint, the prospects for the hybrid vehicle are generally unfavorable. In the smaller vehicles there would be virtually no saving in the cost of the prime mover to offset the extra cost of the generator, electric motors, control system, battery, cabling, etc. of the hybrid. The nickel-cadmium battery, whose present technical capabilities make the hybrid vehicle an immediately feasible proposition, is too expensive at $3/lb and could not be manufactured in the required quantities because of insufficient supplies of cadmium. Although they obviously face a prolonged period of development, high-temperature alkali metal batteries could eventually prove feasible for hybrids; however, their energy density would make them even more attractive as the sole power source of a purely electric vehicle, which is inherently a less complex and thus less costly solution.

There appears to be one possible exception to these negative conclusions. In the case of the city bus, the largest of the vehicle types considered, existing lead-acid batteries have a power density adequate for the hybrid. In the diesel-powered version, the cost of the battery might be about $3000-$4000, an acceptable figure in comparison with average total costs of about $30,000 for conventional full-sized city buses. The slight reduction in the size of the engine would produce a small saving to offset the cost of motors and controls in this size range, but the economic attractiveness, if any, would probably come from lower fuel and maintenance costs, which are always important in commercial/industrial applications. Enthusiasm for the hybrid city bus is, however, tempered by these facts: 1) it is still basically an internal-combustion-powered vehicle and will contribute to air pollution, and 2) the number of buses is relatively small, so the elimination of their pollutants would make only a small contribution to solving the overall problem.

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VII. PROSPECTS AND REQUIREMENTS FOR ELECTRIC VEHICLES

This section reviews the prospects for the six classes of electric vehicles, mainly in terms of the ability of the projected state of the art in electrochemical power sources to meet their technical requirements within an acceptable level of cost. The future technology of motors and controls can be projected with somewhat greater confidence, although cost estimates are based on large extrapolations and are, at best, very approximate. Some consideration is also given to the problems relating to the refueling of electric vehicles.

The findings of this study indicate the technical areas where most effort is necessary if the development of electric vehicles is to be accelerated. From these findings, and taking into account the anticipated progress of existing research and development programs in both the public and private sectors of the economy, a number of recommendations are made concerning the emphasis and direction of future effort.

A. TECHNICAL PROSPECTS

The general technical capabilities of the various electrochemical power sources considered in Section V are summarized in Table 6 on the basis of values that might be attained when the systems now under development reach maturity. While these generalized figures may not accurately apply to some individual systems, they will suffice for a first analysis of vehicle requirements.

1. Family Car

	Conventional		Lightweight	
Requirements:	**Battery or Fuel Cell**	**Gas Piston Hybrid**	**Battery or Fuel Cell**	**Gas Piston Hybrid**
Energy Density (w-hr/lb)	135	–	87	–
Power Density (w/lb)	94	92	60	48

The technical requirements for the power source of the family car are the most demanding of those for all six types of vehicles considered. This is somewhat discouraging, since vehicles in this general category comprise approximately 80% of all vehicles on U.S. highways and are thus responsible for a correspondingly large proportion of the air pollution caused by vehicles. It is apparent from the requirements shown in Table 1 that only the high temperature alkali metal batteries have any prospects of simultaneously satisfying the energy density and power density needs of this vehicle, regardless of the kind of construction. While a number of the metal-air batteries might, with further development, meet the requirements for energy density in the family car with lightweight construction, they cannot meet the power density requirement. The same is true for fuel cells, and particularly so for organic electrolyte batteries.

TABLE 6

GENERALIZED TECHNICAL PARAMETERS FOR ELECTROCHEMICAL POWER SOURCES

System	Maximum Energy Density (w-hr/lb)	Maximum Power Density (w/lb)
High temperature alkali metal batteries (rechargeable)	> 100	> 100
Metal-air batteries (rechargeable)	50-80	30-40
Alkali metal batteries with organic electrolytes (rechargeable)	75-100	15-20
Lead-acid	15-20	20-30
Special construction		60
Nickel-cadmium	15-20	75-100
Special construction		300
Fuel cells	–	30-40

As shown in Section VI, the power density requirements for a mechanical-electrical hybrid in a family car are not much lower than for the purely electrochemical power source. They can, of course, be satisfied by high-temperature batteries and also by the nickel-cadmium battery, but the costs of the former are uncertain and those of the latter are known to be too high. Pile-type lead-acid batteries, if their further development is successful, might also be marginally capable of meeting the hybrid power source requirements for the family car.

Among electrochemical hybrid systems the power density of air-breathing fuel cells is likely to be too low to allow the hybrid to provide a sufficiently high power density, even in combination with high-power-density batteries. The high energy density of the lithium-organic electrolyte battery in hybrid combination with a high rate nickel-cadmium battery could satisfy the technical requirement; this is unlikely to be a suitable power source, however, because of the particularly formidable technical problems associated with the development of rechargeable lithium-organic electrolyte batteries and the unavoidably high cost structure that this system would entail.

Thus, with the marginal exceptions noted above, it can be concluded that high temperature alkali metal batteries are the only electrochemical power sources which appear technically suitable for use in the family car.

2. Commuter Car

	Conventional		**Lightweight**	
Requirements:	**Battery or Fuel Cell**	**Gas Piston Hybrid**	**Battery or Fuel Cell**	**Gas Piston Hybrid**
Energy Density (w-hr/lb)	41	–	28	–
Power Density (w/lb)	46	38	31	23

Power source requirements for the commuter car are less stringent than for the family car. Besides being a lighter vehicle and having lower acceleration capability, it has only one-half the range; as a consequence, the energy density requirement is about one-third, and the power density requirement is about one-half, those of the family car. High-temperature alkali metal batteries should be able to meet these requirements with ease. Metal-air batteries would have adequate energy density capability, but the maximum power density required in the commuter car with conventional construction is somewhat above the upper range of the expected capability of devices using air cathodes. With lightweight construction, the power source requirements should fall easily into the range of capabilities of metal-air batteries and also of fuel cells.

Among hybrid power sources, a high-power-density battery in combination with a fuel cell, lithium-organic electrolyte battery or an engine-generator would all qualify. The power requirements are, however, too high for existing lead-acid batteries, and nickel-cadmium batteries are unacceptable on the grounds of cost and material availability.

6. City Bus

	Conventional		Lightweight	
Requirements:	Battery or Fuel Cell	Gas Piston Hybrid	Battery or Fuel Cell	Gas Piston Hybrid
Energy Density (w-hr/lb)	81	–	55	–
Power Density (w/lb)	36	25	25	15

The city bus with conventional construction has a high energy density requirement, a consequence of the frequent stops in its driving cycle and the value assumed for the range (which may be rather high for city driving service). The power density requirement of 36 w/lb is comparatively moderate. High-temperature alkali metal batteries are capable of meeting both energy density and power density requirements, and the latter is also within the range of metal-air batteries. A relaxation of the range specifications would thus allow the latter system to be an acceptable power source for the city bus. With lightweight construction, the power source requirements should be well within the range of capabilities of metal-air batteries.

Hybrid systems offer some attractive possibilities for the city bus. For both conventional and lightweight construction and for the three types of prime movers, power density requirements calculated for the battery are within the range of lead-acid systems. The hybrid bus system thus appears to be feasible using components from existing technology which are likely to have an acceptable cost.

B. COST FACTORS

1. Considerations of First Cost

Cost estimates for the classes of electric vehicles under consideration in this study involve even greater uncertainties than in the evaluation of the technical factors. It is clear that no vehicle, electric or otherwise, has any prospect of becoming competitive until it is manufactured and marketed on a scale generally comparable with that of today's conventional vehicles; for passenger cars, the minimum level may be of the order of 100,000 units annually. Even then, it seems very likely that the electric vehicle will have a significantly higher first cost. As a broad approximation, fuel costs may be about the same for both electric and internal-combustion-powered vehicles when allowance is made for the heavy fuel tax on refined petroleum products.

A higher first cost may be acceptable for commercial vehicles, where the well recognized lower maintenance and longer life of electric vehicles will be a partial offset. But for commercial and especially for private vehicles it will be necessary to regard the increased expenditure as a social cost attributable to the necessity of eliminating sources of air pollution. In these circumstances the desirability of electric vehicles must, of course, be evaluated in comparison with other potential solutions to this problem.

2. Family Car

Some broad perspectives on the costs of electric vehicles can be obtained by following the same general approach as for the technical factors, namely by taking an existing vehicle and considering which components should be replaced in the conversion from a conventional to an electric power source. If we take the family car as an example and assign to it a factory price of $1400, some $500 might be eliminated by removal of the engine, transmission, gearbox, and other ancillaries directly related to the use of an internal combustion power plant. Replacement of these by electric motors, SCR controllers, speed reducers, cabling, etc., according to the specifications shown in Table 4 would, on the most optimistic assumptions, add approximately $650 back to the cost. (This is based upon cost estimates per vehicle horsepower of $4 for a dc commutator motor, $2 for the controller system and $1 for cabling and miscellaneous; see Section IV.)

Thus even before we consider the cost of the power source, the factory price of the electric vehicle would already be some 10% higher than that of a conventionally powered car. The cost which can be tolerated for the power source is thus a rather subjective quantity, as there are clearly no savings to demonstrate. In our opinion, an electric family car might be justifiable if its retail price were not more than approximately $1000 over that of a corresponding conventionally powered vehicle. Since average distribution costs should be unchanged, this would translate into a permissible increase of $1000 in the factory price.

Such a differential might be regarded as a premium for longer life and lower maintenance, but for private cars, some further incentive – probably in the form of selective taxation – would almost certainly be necessary. While $1000 is a relatively large sum today, the period under consideration is in the 1980's at the earliest, due to the time required for technical development and cost reduction. By then, personal affluence should have increased to an extent that such additional expenditure might be much less significant.

If the allowable weight for the battery in an adequately powered family car with conventional construction is 900 pounds (Table 1) the allowable factory cost for the battery must be in the region of $0.95/lb. With lightweight construction the allowable cost per unit weight of a battery just meeting specifications would be lower than this, for two reasons: 1) it would be heavier (~1400 pounds), and 2) the use of lightweight nonferrous metals for structural members and plastic materials for body panels is likely to increase the manufacturing costs, leaving less money to be spent on the battery. In this situation, to meet the cost criteria we have set, a figure of $0.50/lb is probably all that could be tolerated.

These estimates are somewhat clouded by the question of battery replacement, since it is unlikely that the life of the battery will be as great as that of the rest of the vehicle. Costs amortized over a five-year period are probably low enough to be written off against operating costs, but it must be recognized that a five-year lifetime introduces a significant new technical requirement for the battery.

The commuter car thus appears also to require high-temperature alkali metal batteries, but rechargeable metal-air batteries would appear to have prospects of providing an adequate alternative.

3. Utility Car

	Conventional		Lightweight	
Requirements:	**Battery or Fuel Cell**	**Gas Piston Hybrid**	**Battery or Fuel Cell**	**Gas Piston Hybrid**
Energy Density (w-hr/lb)	26	–	18	–
Power Density (w/lb)	40	34	28	20

The requirements for the utility car are the most modest of the series. Considering first the requirements for lightweight construction, the power source needs can be met by lead-acid batteries of the type representative of the best of today's technology and comfortably within what normal evolution should provide within a few years. With conventional construction the utility car has a rather high power density requirement, close to the upper range likely to be achieved by metal-air batteries. High-temperature alkali metal batteries, of course, easily satisfy all requirements of the utility car.

While a number of hybrid power source systems, both mechanical-electrical and electrochemical, are technically feasible power sources for the utility car, their complexity makes them inappropriate for such a small vehicle.

Thus, improved lead-acid batteries would seem to be technically adequate for this vehicle application; the higher performance metal-air batteries and high-temperature alkali metal batteries offer potential alternatives whose merit might be determined on the basis of cost.

4. Delivery Van

	Conventional		Lightweight	
Requirements:	**Battery or Fuel Cell**	**Gas Piston Hybrid**	**Battery or Fuel Cell**	**Gas Piston Hybrid**
Energy Density (w-hr/lb)	50	–	33	–
Power Density (w/lb)	55	43	36	25

The requirements for the delivery van with conventional construction show the need for a relatively high power density of 55 w/lb. This is likely to be above the developed capabilities of the metal-air battery systems and of fuel cells. As in the case of the family car, it would appear that the delivery van will require high-temperature alkali metal batteries as its power source. In a hybrid with a gas piston engine, the power density requirement for the battery falls to 43 w-hr/lb, but this is still attainable only by the high-temperature and nickel-cadmium batteries.

With lightweight construction, however, the power source requirements for the van fall into a range likely to be attained by metal-air batteries, and in the gas piston hybrid vehicle the battery requirements might be accommodated by the lead-acid system.

While high-temperature alkali metal batteries seem in general to be the indicated power source for the delivery van, it is evident that a much wider range of possibilities would be opened up through the use of lightweight construction.

5. City Taxi

	Conventional		**Lightweight**	
Requirements:	**Battery or Fuel Cell**	**Gas Piston Hybrid**	**Battery or Fuel Cell**	**Gas Piston Hybrid**
Energy Density (w-hr/lb)	96	–	64	–
Power Density (w/lb)	45	35	30	22

For the city taxi the energy density requirement is high, since it is equivalent to that of the family car but scaled down in proportion to its somewhat shorter range. The lower acceleration performance demanded of the city taxi, however, reduces the power density requirement to less than one-half of that for the family car. With conventional construction, this reduced power density still seems to be above the expected capability range for the rechargeable metal-air batteries, and high-temperature alkali metal battery systems again appear necessary. In a hybrid vehicle with a gas piston engine, the nickel-cadmium battery would be satisfactory, and improved lead-acid batteries might also meet the power density requirements.

With lightweight construction, metal-air batteries should be capable of meeting the power source requirements for the city taxi, although the energy density specification might be close to the upper limit in some systems. Lightweight construction would also appear to qualify the lead-acid system for inclusion as the battery in the gasoline-powered hybrid system.

6. City Bus

Requirements:	Conventional Battery or Fuel Cell	Conventional Gas Piston Hybrid	Lightweight Battery or Fuel Cell	Lightweight Gas Piston Hybrid
Energy Density (w-hr/lb)	81	–	55	–
Power Density (w/lb)	36	25	25	15

The city bus with conventional construction has a high energy density requirement, a consequence of the frequent stops in its driving cycle and the value assumed for the range (which may be rather high for city driving service). The power density requirement of 36 w/lb is comparatively moderate. High-temperature alkali metal batteries are capable of meeting both energy density and power density requirements, and the latter is also within the range of metal-air batteries. A relaxation of the range specifications would thus allow the latter system to be an acceptable power source for the city bus. With lightweight construction, the power source requirements should be well within the range of capabilities of metal-air batteries.

Hybrid systems offer some attractive possibilities for the city bus. For both conventional and lightweight construction and for the three types of prime movers, power density requirements calculated for the battery are within the range of lead-acid systems. The hybrid bus system thus appears to be feasible using components from existing technology which are likely to have an acceptable cost.

B. COST FACTORS

1. Considerations of First Cost

Cost estimates for the classes of electric vehicles under consideration in this study involve even greater uncertainties than in the evaluation of the technical factors. It is clear that no vehicle, electric or otherwise, has any prospect of becoming competitive until it is manufactured and marketed on a scale generally comparable with that of today's conventional vehicles; for passenger cars, the minimum level may be of the order of 100,000 units annually. Even then, it seems very likely that the electric vehicle will have a significantly higher first cost. As a broad approximation, fuel costs may be about the same for both electric and internal-combustion-powered vehicles when allowance is made for the heavy fuel tax on refined petroleum products.

A higher first cost may be acceptable for commercial vehicles, where the well recognized lower maintenance and longer life of electric vehicles will be a partial offset. But for commercial and especially for private vehicles it will be necessary to regard the increased expenditure as a social cost attributable to the necessity of eliminating sources of air pollution. In these circumstances the desirability of electric vehicles must, of course, be evaluated in comparison with other potential solutions to this problem.

2. Family Car

Some broad perspectives on the costs of electric vehicles can be obtained by following the same general approach as for the technical factors, namely by taking an existing vehicle and considering which components should be replaced in the conversion from a conventional to an electric power source. If we take the family car as an example and assign to it a factory price of $1400, some $500 might be eliminated by removal of the engine, transmission, gearbox, and other ancillaries directly related to the use of an internal combustion power plant. Replacement of these by electric motors, SCR controllers, speed reducers, cabling, etc., according to the specifications shown in Table 4 would, on the most optimistic assumptions, add approximately $650 back to the cost. (This is based upon cost estimates per vehicle horsepower of $4 for a dc commutator motor, $2 for the controller system and $1 for cabling and miscellaneous; see Section IV.)

Thus even before we consider the cost of the power source, the factory price of the electric vehicle would already be some 10% higher than that of a conventionally powered car. The cost which can be tolerated for the power source is thus a rather subjective quantity, as there are clearly no savings to demonstrate. In our opinion, an electric family car might be justifiable if its retail price were not more than approximately $1000 over that of a corresponding conventionally powered vehicle. Since average distribution costs should be unchanged, this would translate into a permissible increase of $1000 in the factory price.

Such a differential might be regarded as a premium for longer life and lower maintenance, but for private cars, some further incentive – probably in the form of selective taxation – would almost certainly be necessary. While $1000 is a relatively large sum today, the period under consideration is in the 1980's at the earliest, due to the time required for technical development and cost reduction. By then, personal affluence should have increased to an extent that such additional expenditure might be much less significant.

If the allowable weight for the battery in an adequately powered family car with conventional construction is 900 pounds (Table 1) the allowable factory cost for the battery must be in the region of $0.95/lb. With lightweight construction the allowable cost per unit weight of a battery just meeting specifications would be lower than this, for two reasons: 1) it would be heavier (~1400 pounds), and 2) the use of lightweight nonferrous metals for structural members and plastic materials for body panels is likely to increase the manufacturing costs, leaving less money to be spent on the battery. In this situation, to meet the cost criteria we have set, a figure of $0.50/lb is probably all that could be tolerated.

These estimates are somewhat clouded by the question of battery replacement, since it is unlikely that the life of the battery will be as great as that of the rest of the vehicle. Costs amortized over a five-year period are probably low enough to be written off against operating costs, but it must be recognized that a five-year lifetime introduces a significant new technical requirement for the battery.

3. Commuter Car

For the commuter car the assumed factory price might be $800, with $200 assigned to engine, transmission, etc. Using the same basis for the costs of electric motors and controllers as for the family car, we find that the electrical components are comparably but slightly more expensive than the ones they replace ($210 vs $200). Thus, the cost of the power source can be equated with the extra retail price which we have assumed can be borne by the electric vehicle. If this is set at $500, the cost of the power source in the commuter car with conventional construction must be about $0.75/lb. Such a battery would have less than one-third the energy density and less than one-half the power density of the family car's power source. The performance of a battery capable of meeting the family car's requirements of 135 w-hr/lb and 94 w/lb would support a cost of about $1.90/lb in the commuter car; at $0.95/lb the first cost of the vehicle would be close to that of a conventionally powered vehicle.

4. Utility Car

Since no well-established model exists for a utility car constructed from conventional materials, the permissible cost of the necessary battery can only be estimated by judicious guesswork. Figures of $0.40-0.50/lb and a total cost of under $200 appear to be appropriate.

5. Commercial Vehicles

Somewhat less stringent cost requirements may hold in the commercial vehicle category, since – for the van and bus, at least – production volumes are lower and unit costs relatively higher than is the case for passenger cars. Moreover, since the percentage of operating time is very much higher for commercial than for private vehicles and since the longer life and expected lower maintenance costs are better recognized, a higher cost structure for the battery can be tolerated. Inspection of the data for assignable weight indicates that $1.00-1.50/lb might be a reasonable estimate of the allowable cost for a power source which met the minimum technical requirements for the van, taxi, and bus with conventional construction.

6. Future Cost Structure of Power Sources

The above cost estimates for the vehicle power source, crude as they are, form some basis for an assessment of the prospects of the various power sources. As a point of comparison, it may be noted that today's lowest cost battery system, lead-acid, has an OEM price of approximately $0.25/lb in the high-volume application of automobile starter batteries. This is based upon relatively low-cost raw materials, the most expensive of which is lead at $0.13-0.16/lb, and a very mature manufacturing technology. For the lower production volume and longer-lived industrial lead-acid battery, OEM prices are in the range of $0.50-0.60/lb. Standard types of nickel-cadmium batteries, which are manufactured on a much smaller scale than lead-acid and use high cost materials (the raw materials costs being approximately

$0.80/lb for nickel and $3/lb for cadmium), have a representative cost of about $3/lb in the 0.1 to 1.0 kw-hr size range.

Estimates of the potential cost structure of the new types of batteries now under development are very speculative. Among the high-temperature alkali metal batteries we believe that the capacitive storage device of SOHIO and the sodium-sulfur battery of Ford have prospects of achieving a cost level of approximately $1.50/lb in volume production; this seems to be a sufficiently encouraging basis for anticipating an ultimate price in the $1.00/lb range.

Metallic lithium, presently at $7/lb and with prospects of its price falling 50% as its production volume increases, might seem an expensive element for inclusion in a vehicle battery. However, its low equivalent weight results in a low requirement per battery, and with a lithium content of only 5-10%, the cost of this element should not be prohibitive. The GM lithium-chlorine battery seems likely to have a somewhat higher potential cost structure, less on account of the lithium than on the materials engineering problems associated with the handling of chlorine and the temperature (over 100°C higher than the other systems). The lithium-selenium and lithium-tellurium systems under investigation at the Argonne National Laboratory offer no prospect of developing into low-cost batteries because of the cost and the present scarcity of the cathode materials, selenium and tellurium. The recent work there on a high-temperature lithium-sulfur battery does, however, hold promise of yielding a low-cost battery.

Most of the rechargeable metal-air batteries now under development use acceptably low-cost materials (zinc, sodium, iron) as anodes. While air is free, a significant material cost is involved in the catalysts needed for effective and long-lived air cathodes and for the structural material of the cathode itself if it is to be used for oxygen evolution on recharge.

Electrically rechargeable metal-air batteries fall into two broad classes: those which involve some engineering artifice and those which have a relatively conventional construction. Among the former are the zinc-air batteries of General Atomic and Yardney Electric and the sodium-air battery of Atomics International. Both the zinc-air batteries are of some mechanical complexity, and the sodium-air battery may entail an appreciable materials cost for mercury. While there can be no firm estimates at this stage, the initial costs of these "engineering artifice" metal-air batteries in quantity production might be in the region of $3/lb with good prospects of falling to the $1.50-$2.00/lb region as experience with the systems grows.

Conventionally rechargeable zinc-air batteries, such as those being investigated by Leesona, ESB, Union Carbide, and McDonnell-Douglas, may cost close to $1.50/lb, since they would be of simpler construction. However, the fundamental technical problems associated with the recharging of the zinc electrode are so great that such batteries may never attain a cycle life acceptable for vehicle applications.

The characteristics of mechanically rechargeable metal-air batteries developed by Leesona in the zinc-air system, and considered conceptually by Atomics International for sodium-air, are not sufficiently established for conclusions to be drawn about their applicability to vehicles. When their technology matures, first costs are likely to be comparable with those of other metal-air batteries; but operating costs will depend largely on the economics of reconstituting spent anodes, probably at centralized service stations, and at present these appear to be unfavorable. This type of battery would be attractive, however, if it could be recharged electrically in regular service and mechanically recharged only during an occasional long trip.

The very approximate cost criteria which we have set for electric vehicles would appear to eliminate the prospects of the fuel cell, either as the sole power source or in a hybrid combination with batteries. A fuel cell is inherently a more complex and thus more costly device than a battery, because it has to accommodate the orderly passage of materials across its boundaries in addition to heat and electricity. Moreover, there is as yet no indication that fuel cells whose performance is adequate for vehicular application will not require precious metal catalysts. Because of these limitations, ambient-temperature fuel cells seem unlikely to attain an ultimate cost structure of less than $2 to $3/lb. Although high-temperature fuel cells will probably have lower costs, their power densities appear to be too low. Any equipment required for pre-treatment of the fuel, such as reforming or thermal cracking, will add further to the first costs.

Some general comments on the costs of hybrid systems have already been made in Section VI. If the hybrid is to be considered as a substitute for the conventional vehicle power plant, it is apparent that the cost of the engine, generator and battery must be compared with that of the battery or fuel cell of the purely electric vehicle. If we use the family car as an example and apply the cost criteria for the gasoline piston engine shown in Figure 12, the engine-generator costs for a 40-60, prime mover-battery hybrid would be about $500 (allowing about $2/kw for the ac generator rectifier and speed increaser). With $650 assigned to motors and controllers, offset by only $500 for the replaced engine transmission, gearbox, etc., the net extra cost is $650 plus that of the battery. If the total cost is to be kept within $1000 of the cost of a conventionally powered family car, it is apparent that the cost of the necessary 51-kilowatt battery, weighing not more than 550 pounds, must be $350 or less. Only the high-temperature alkali metal batteries and the nickel-cadmium system have prospects of this technical capability, and in this situation the latter is, of course, too expensive by a factor of at least five. The cost criteria for the alkali metal battery used in a hybrid system are somewhat more demanding than when this battery is used in a purely electric vehicle, so that when such batteries become available there would seem to be no incentive for using them in hybrids.

As previously noted, the best prospects for the hybrid vehicle appear to lie with the commercial vehicles, and particularly the city bus. The calculations of Section VI indicated that a 5000-pound battery with a power density of 29 w/lb (or less if lightweight construction is used) would be adequate in a diesel-powered hybrid. It should be possible for a specially designed lead-acid battery to meet these criteria, using existing technology, for a cost of about $3000. Such a hybrid-powered bus would undoubtedly have higher first costs than a conventional bus, but the percentage increase should be substantially less than for the smaller vehicles.

To summarize, it seems apparent that electric vehicles are likely to have higher first costs than conventional vehicles, even in high-volume production and with maturation of the contributing technologies. Some of this cost differential may be acceptable on the basis of lower operating costs due to a reduced maintenance requirement and longer life, but most must be attributed to the social benefits of decreased air pollution. On the assumption that an additional $1000 might be placed on the retail price of the family car and perhaps an additional $500 for the commuter car, high-temperature alkali metal batteries appear to offer the best chances of meeting the cost criteria. Metal-air batteries will probably have a somewhat higher cost structure and be acceptable only in commercial vehicles. Fuel cells are likely to be too expensive, and mechanical-electrical hybrid systems appear promising only in the case of the city bus.

C. REFUELING

It is apparent that the large-scale introduction of electric vehicles would have a major impact on a number of important sectors of the national economy. This study, however, is concerned with the technology of the vehicle itself; the effects of the large increase in the use of power on the electrical generating industry,* the changes in the demand for materials, the impact on the petroleum industry, and the effect on the myriad of ancillary suppliers to the vehicle manufacturers are outside its scope. Consideration is given to the question of vehicle refueling, however, since it has direct bearing on the selection of the vehicle power source.

Present-day conventional vehicles are refueled by the simple expedient of filling their tanks with gasoline or diesel oil as appropriate. The whole operation can be carried out in five to ten minutes. There would be no change in procedure for a mechanical-electrical hybrid, and an equivalent procedure is possible for a fuel-cell-powered system, although the nature of the fuel might set some special restrictions. A vehicle powered entirely by batteries, however, clearly needs a totally different method of refueling. This problem has been considered in terms of the three general options of rapid recharge, slow recharge, and mechanical replacement.

Rapid recharge would involve the acceptance of a full charge by the battery within a period of ten minutes or so, comparable to the time it takes to refuel a conventional vehicle. A moment's consideration suggests that this mode of recharge is rather impractical. To recharge the battery in the family car in ten minutes would require a power source with a dc output of approximately one megawatt (allowing for inefficiencies). While we have not determined the probable capital costs of a dc rectifying system with this power capability, it is likely to be excessively high, even when manufactured on a large scale. Moreover, such a requirement for power would be likely to invoke a demand charge from the supplying utility. The implications for the vehicle itself are even more severe. Factors such as safety, insulation, and the cost of batteries are likely to hold the voltage of its electrical system to a maximum of 500 volts. At this voltage, the wiring in the vehicle would need to carry a current of about 2000 amperes during recharge, which would require heavy and costly quantities of copper cabling. A further consideration is the large and probably damaging amount of heat generated in the battery due to the inefficiencies of the charging processes.

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*Complete conversion to electric vehicles today would create an additional load averaging about 40% of present electrical power consumption.

From the standpoint of battery technology, rapid recharging would be feasible only for systems having the highest power density. The ratio of maximum energy density to maximum power density, having the units of time, is a good index of a reasonable minimum recharging period for a battery. For this to be as low as ten minutes, the ratio must be less than 1:6; only the nickel-cadmium battery and possibly the SOHIO system seem likely to meet this criterion.

Slow recharge of a battery is considered to mean a charging period of from four to perhaps eight hours. The obvious time for this is at home overnight, or possibly at metered outlets when the vehicle is parked during the day. The rectifying equipment could be either on the vehicle or at the outlet. The advantages to this approach are the converse of the disadvantages of rapid recharge: slow recharging involves a very much lower investment cost in recharging equipment, the weight and cost of cables on the vehicle is less, the electrical efficiency is higher so that energy is conserved, there is less damage to the battery due to heating, and its lifetime is consequently lengthened. Home recharging also has the great advantage of making the motorist independent of visits to a service station, at least for refueling, and it would have the desirable effect of spreading the load on the electrical generating system largely onto the off-peak hours.

The obvious disadvantage of slow recharge is that the vehicle is unusable for a substantial part of the time. This probably would not be a serious difficulty, since the great majority of trips are undertaken for relatively short distances and on a fairly fixed daily schedule. Longer trips might depend on exchanging depleted batteries for fully charged ones at service stations, which raises questions of ownership and of battery standardization. Battery leasing with a metered use charge, might well be the procedure adopted. Maintenance work on batteries, such as occasional electrolyte replacement in alkaline systems, might be carried out during their residence time in the service stations.

For batteries with air cathodes an alternative to replacing the batteries on extended trips is the replacement of the anode alone. However, this procedure is certainly more complex and probably more costly.

It thus appears that the formidable technical difficulties associated with rapid recharging make slow recharging the necessary method of refueling, with mechanical substitution of batteries being used to extend the range on occasional long trips. This arrangement is less than ideal, but it appears to have enough advantages to make it acceptable.

D. SUMMATION AND RECOMMENDATIONS

The general conclusion to be drawn from this analysis of the requirements for electric vehicles is that the necessary technology appears attainable, and that the cost of electric vehicles, while higher than that of conventional vehicles, might still be acceptable. A very substantial technical effort is called for if the required technologies are to be brought to maturity. One of the objectives of this study is to identify areas in which more effort might profitably be made.

For the electric vehicle to achieve performance broadly comparable to that of today's internal combustion powered cars, a low-cost, high-temperature alkali metal battery must be developed. The major virtues of this class of battery are their high energy density, which is a consequence of the high reactivity of the alkali metals, and their high power density, due to the rapid rate at which the electrochemical reactions take place at the elevated temperatures. Since the alkali metals are well above their melting point in these batteries, many technical problems of anode recharging are avoided. Of the alkali metals, only lithium and sodium are serious candidates: lithium because it is the lightest, and sodium because it is the cheapest. Calcium, although having a high melting point (840°C), might provide an alternative anode material for high-temperature batteries; no work has been done in this area, however. Among cathode materials the most promising elements are sulfur and chlorine. It is also possible that phosphorus might be acceptable but its electrochemical properties are almost completely unexplored.

Bringing the technology of high-temperature alkali metal batteries to maturity will obviously be no easy task, since very formidable problems in materials selection and safety are evidently involved. Much engineering inventiveness will be required in the development of auxiliary heaters and insulation in the systems for temperature control, these complexities being appropriate only for batteries of the size capable of powering vehicles. The public acceptance of high temperature alkali-metal batteries is also a major question: the presence of a 900-pound battery containing alkali metals and elements such as chlorine or sulfur at a temperature possibly as high as 600°C is obviously not a particularly desirable feature for the family car. Effective, low cost insulating materials are clearly essential, and the design must make the battery as crash-proof as possible. Groups presently developing batteries in this class are optimistic that this can be done.

Given the requirement that the performance of a conventional vehicle must be matched, metal-air batteries appear to be too power-limited for application in the family car. They are likely to be somewhat more costly on both a weight and performance basis than the high-temperature systems, although neither technology is advanced enough to generate firm cost estimates. Metal-air batteries do, however, appear to have reasonable prospects for the commercial vehicles, particularly if advances are made in the utilization of lighter structural materials. The metal-air batteries in general have a major advantage in that they operate at temperatures close to ambient. For these reasons, further development of the metal-air systems seems fully justified. Moreover, there are prospects that the pattern of transportation, particularly in the cities, may change sufficiently in the future in the direction of smaller and less powerful vehicles so that the metal-air battery would provide a completely adequate power source.

Alkali metal batteries using organic electrolytes share the large advantage of operation at ambient temperatures and have high energy density, but their power density is low. The major problems limiting their future potential as a vehicle power source are the questions of whether they can ever be recharged at practical current densities and whether they can achieve an adequate cycle life. As in the metal-air batteries, it is conceivable that mechanical artifices might be introduced into these systems to overcome the electrochemical problems, but as yet such approaches have not been investigated. In view of its relatively less attractive prospects this class of battery does not appear to merit a major effort to adapt it for use as a vehicle power source. However, it will undoubtedly see further development in view of its potential applications in other areas.

Prospects for the fuel cell as a vehicular power source are rated as unfavorable partly because of its power density limitation but mainly because of its inherently greater complexity and cost relative to batteries. There thus seems to be no justification for a fuel cell development program oriented exclusively toward civilian highway vehicles, although fuel cells might well find vehicle applications in the military or specialized industrial fields.

Our consideration of the technology of electric motors and controllers shows that vehicular requirements are certainly attainable and, in fact, can be largely met today. The major development effort for the future relates to the lowering of costs to a level acceptable for the vehicle application. The opening up of such a large market for these components would be a strong incentive for manufacturers to make such cost reductions, but it is evident that specifically oriented research programs will be needed to devise production techniques that will yield the extremely low unit costs demanded.

Any formulation of recommendations for additional research and development programs in the technologies relating to electric vehicles must take into account existing and planned programs in these areas by other agencies, both public and private. A considerable budget is already allocated by the government for support of research and development on electrochemical power sources and the electrical technologies relating to motors and controls. The two agencies most involved are the Department of Defense and NASA.

Within the Defense Department the greatest expenditures are by the Army. Programs carried out and sponsored by the Engineering Research and Development Laboratory at Fort Belvoir, Virginia, have been concerned with novel electrical propulsion systems for military vehicles, with emphasis on gas turbine generators and fuel cells as the power sources. Support has been given to work on fuel cells using hydrocarbons (either directly in high-temperature systems or via a reforming or thermal cracking step), fuel cells using hydrazine, and various development programs concerning electric motor and control systems, both ac and dc, which might be employed. The Army Tank Automotive Command at Warren, Michigan is also working on electrical systems development, complementing the work at Fort Belvoir. At the Electronics Command at Fort Monmouth, N.J., support has been given to work on fuel cells and on metal-air and lithium-organic electrolyte batteries. The latter is concerned mainly with primary batteries and is thus of little relevance to vehicles.

Work supported by the Navy has included programs on lithium-organic electrolyte primary batteries and on the identification of more effective and lower cost catalysts for ambient-temperature fuel cells. The Navy is also concerned with the technology of advanced high speed electric motors, primarily for torpedo application.

The Air Force has supported most of the earlier work on rechargeable lithium-organic electrolyte batteries; it has also supported work on metal-oxygen batteries (which are closely related to the metal-air systems), and on fuel cells and rechargeable batteries for satellite applications. Much of the initial development of static inverter technology was carried out under Air Force sponsorship.

NASA's work in electrochemistry and electrochemical engineering includes the sponsorship of major fuel cell programs and related support for manned spacecraft power sources and the development of improved sealed, rechargeable batteries, particularly high rate nickel-cadmium and silver systems for satellite application. NASA has also supported a good deal of work on lithium-organic electrolyte primary batteries, some on metal-oxygen systems, and has also been active in static inverter technology.

Total expenditures by all government agencies for research and development in the field of electrochemical power sources have been estimated at approximately $10 million annually, exclusive of the large fuel cell hardware projects relating to the Apollo manned spacecraft program. Expenditures of a further $5 million or so can probably be attributed to developments in the motors and controls field that have some bearing on the technology of electric vehicles. This latter figure includes estimates for that portion of the electric transmission systems developed for high-speed rail transportation which are applicable to self-propelled electric vehicles. The size of these amounts naturally varies with the definition of the relevance of the program and fluctuations in contract appropriations from year to year.

It is also important to recognize that most of the federally sponsored programs have been focused on such different objectives that they have only a very limited contribution to make to the development of commercially viable electric vehicles. Thus, while NASA fuel cell programs have demonstrated that efficient and reliable fuel cells with electrical outputs of several kilowatts are feasible, the details of the technology are not translatable into the needs of a mass-produced, low-cost power source. Similarly, the work on vehicle systems being carried out by the Army naturally focuses on military field situations which involve specific requirements very different from those of the civil environment. When the specific content of the programs are taken into account, it can be seen that only a small proportion of the federal expenditures are applicable to the problems of civilian electric vehicle development.

An account of private research effort in power source development has been given in the body of this report. An overall figure can only be a crude estimate, but it would appear that expenditures by U.S. private industry on novel power source development relating to electric vehicles total $5-7 million annually. A substantial fraction of this is represented by the programs of the two major automobile manufacturers, and a proportion of the remainder is invested in anticipation of later support from federal agencies.

The magnitude of the technical problems involved in the development of batteries capable of meeting vehicle power source requirements and the increasing urgency of air pollution abatement in the cities both point to the need for an acceleration of technical effort if electric vehicles are to be an effective solution. If the assumptions about vehicle performance made in this study are correct, the major effort should clearly be directed toward extension of the scale of work on high-temperature alkali metal batteries. The existing work in this area at GM, Ford, SOHIO, and Argonne National Laboratory is valid and valuable, but considering the magnitude of the technical problems and the massive implications of the development, a more comprehensive and coordinated program appears to be needed.

Such a program might involve basic electrochemical studies of all elements that have prospects of satisfying both technical and cost criteria for the vehicle battery; these should include lithium, sodium, and possibly calcium, magnesium, and aluminum as anodes and sulfur, chlorine, and possibly phosphorus as cathodes. The prospects of air cathodes in high temperature systems should also be evaluated, and for completeness some attention should be given to the potentialities as cathodes of the halides and sulfides of the transition metals. An important part of the program would be the characterization of the molten salt and ceramic systems which would be the electrolytes of these batteries. Other work should focus on the materials selection and engineering problems of the battery. Noncorrodable conductive materials for current collectors and suitable inorganic materials for separators and supporting structures, sealants, and insulating materials are all needed. Materials selection and engineering design optimization are usually specific to a particular battery system, so that the initial work should be concentrated as far as possible on developments having the greatest general application. The technology of low-cost thermal control systems, heaters, and insulation is another important area.

The other major technical area deserving additional support is that of rechargeable metal-air batteries. While their projected performance is not adequate for the most demanding of the vehicle applications, it may well be acceptable for the types of vehicles which may evolve from new patterns of transportation within the city. The technical problems of directly rechargeable metal-air batteries will respond, if at all, to increased emphasis on the basic electrochemistry of the systems. The engineering solutions such as those being worked on at General Atomic and Atomics International can, however, be supported at the development stage, since their difficulties are of a less fundamental nature. Further work on the problem of developing low-cost catalysts for air cathodes is desirable and such work would also contribute to fuel cell technology.

In the area of motors and controls the development of low-cost manufacturing techniques for components and systems should be encouraged; the technology is already in existence, but the chief emphasis has been on specialized, low-volume applications where cost is not important. While the prospect of large commercial markets will certainly stimulate private research expenditures in this field, some judicious seeding of development funds could bring the technologies more sharply into focus for electric vehicle applications.

In summary the technology of electric vehicles appears to be attainable, quite possibly at an acceptable cost. But this is unlikely to come about in less than ten to fifteen years and then only if substantial efforts are made at the present stage in the planning and execution of programs – particularly in the field of power source development – which are specifically oriented toward the performance and cost parameters demanded by the vehicle application. The technical risks of this endeavor are too great for the investment to be borne by private capital alone, particularly since the major objective is a technology desirable for its social good rather than for its profit potential.

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APPENDIX A

NOTES ON ELECTRIC VEHICLE DEVELOPMENT IN THE UNITED STATES

While electric automobiles represented a significant proportion of all highway vehicles in the early 1900's, they had been almost completely displaced by the 1920's, due to improvements in the internal combustion engine. Apart from some occasional attempts to market small specialized electric cars, the only continuing commercial activity in recent years, relating to highway vehicles, has been the manufacture of electric delivery trucks by the Battronic Truck Corp., a company jointly owned by the Boyertown Auto Body Works, ESB, Inc., and Smith's Delivery Vehicles Limited, a major British manufacturer. Gould-National Batteries, Inc., manufactured a line of electric trucks in the mid-1950's, but discontinued the activity due to lack of demand. Cushman Motors, Inc., manufactured a dozen small, three-wheel vehicles powered by lead-acid batteries for the Post Office Department in 1959, and four larger vehicles were purchased in 1962 from a division of ESB, Inc. At about the same time, National Union Electric Corporation converted some 50-60 Renault Dauphines to electric drive, the product being called the "Henney Kilowatt." Electric utility companies bought many of them, and several have been the subject of further conversions described below. While not highway vehicles, electric golf carts are, of course, a flourishing product, and personnel carriers for use at airports, resorts, and large industrial plants are becoming commonplace.

Over the last few years there has been considerable activity in experimental electric vehicle development, mainly in anticipation of their much wider use in the future. This Appendix contains notes on some of these activities.

A. AMERICAN MOTORS CORPORATION – GULTON INDUSTRIES

AMC and Gulton have announced a joint program to develop a small electric car making use of a hybrid combination of Gulton's lithium-nickel fluoride batteries and high-power-density bipolar nickel-cadmium batteries (a concept described in Section V). The vehicle will seat three persons and weigh about 1100 pounds. The power sources will be two 75-pound lithium batteries for energy storage and two 25-pound nickel-cadmium batteries to provide adequate power. With regenerative braking, a 150-mile range is projected. The limiting feature to this development would appear to be the state of the art in lithium batteries, which have as yet not demonstrated a convincing degree of rechargeability in practical battery configurations nor an adequate shelf life.

B. ELECTRIC FUEL PROPULSION, INC.

This small company is manufacturing electric cars by conversion of the conventionally powered Renault-10. The power source is eight 12-volt, 205 amp-hour (5-hour rate) lead-acid batteries weighing approximately 1600 pounds. The batteries contain a cobalt additive which is claimed to reduce grid corrosion and thus give relatively longer life at high charging rates. The car is heavy–4040 pounds curb weight compared with 1735 pounds for the original Renault-10–but the performance specifications are quite impressive: 0-40 mph in 12 seconds, a maximum speed of 60 mph and a range of 70-120 miles under city driving conditions. The car has a regenerative braking system. A substantial number (now approaching fifty) of these cars have been purchased or are on order by electric utilities and other companies interested in the electric propulsion field. Their evaluation should provide some valuable data on the operating costs of highway vehicles powered by lead-acid batteries.

C. ESB--BATTRONIC

As mentioned above, ESB, Inc., participates in the electric highway vehicle field via its part-ownership of Battronic Truck Corp. The principal product of the latter company is a delivery truck having a loaded gross weight of 9500 pounds. The load and battery weight combined are 5000 pounds and can be mutually adjusted to suit the route requirements within load limits of 2000 to 3000 pounds. The batteries used are 84-volt lead-acid systems with capacities of either 425 or 340 amp-hours. The range of the vehicles is about 40 miles with a top speed of 25 mph.

ESB also operates a converted Renault Dauphine of the Henney Kilowatt type. This vehicle is powered by twelve 6-volt golf cart batteries rated at 140 amp-hours (5-hour rate), which give it a maximum speed of 40 mph, a range of 25 to 35 miles, and an acceleration of from 0 to 29 mph in 3 seconds.

D. FORD MOTOR COMPANY

Published reports of Ford's activities with experimental vehicles are confined to its work with the "Comuta," a small vehicle built by English Ford, one of which has been shipped to Ford's Dearborn headquarters. Comments on the Comuta are included in Appendix B.

E. GENERAL ELECTRIC

In October 1967, General Electric announced that it had built an experimental car having a maximum speed of 55 mph on level ground and a range of 40-50 miles under normal stop-and-go driving. The vehicle, which had a magnesium frame and a fiberglass-polyester body, weighed 2300 pounds and could carry two adults and two children. A novel feature was the use of lead-acid batteries as the main energy source with nickel-cadmium batteries in parallel to provide power for acceleration and hill climbing. The combined weight of batteries in the hybrid power source was about 40% of the vehicle's curb weight.

F. GENERAL MOTORS

General Motors Corporation has constructed two full-size electric vehicles primarily for use as test beds—the Electrovair II, a converted Corvair powered by silver-zinc batteries, and the Electrovan, a converted GMC Handivan powered by a hydrogen-oxygen fuel cell. Both vehicles have substantially the same motor and control system, a novel, lightweight, high-speed (13,000 rpm) ac squirrel cage induction motor. This motor, which weighs 130 pounds and is capable of delivering a maximum of 1.3 horsepower per pound, receives power from a thyristor inverter. The present weight of the controls, however, tends to eliminate the weight advantage of the motor system used; the electrical system has a total weight of 550 pounds. The voltage of the system, 530 volts, is the highest used in any electrochemically powered vehicle.

Both vehicles were designed to have substantially the same performance as their conventionally powered counterparts. In the case of the Electrovair II, this meant an acceleration of 0 to 60 mph in 16 seconds and a top speed of 80 mph. The Electrovair's silver-zinc batteries, provided by Yardney Electric, weigh about 650 pounds and give a range of 40-80 miles under normal driving conditions. The hydrogen-oxygen fuel cell in the Electrovan was manufactured by Union Carbide and operates on cryogenically stored fuel and oxidant. It has a continuous power rating of 32 kw. A favorable characteristic of fuel cells is their capability of responding to temporary overload; the fuel cell in the Electrovan has an overload capability of up to 160 kw. Both vehicles are much heavier than their conventionally powered counterparts: 3400 pounds versus 2600 pounds for the Electrovair and 7100 pounds versus 3250 pounds for the Electrovan.

G. GOULD-NATIONAL BATTERIES, INC.

In cooperation with North Star Electric, a Minnesota electric utility, Gould-National has recently modified two Henney Kilowatt Renault Dauphines with improved battery and control systems. The original twelve 6-volt, 180 amp-hour golf cart batteries were replaced with eighteen 12-volt, 80 amp-hour automotive starter batteries of newly improved design, having a polypropylene case, internal connectors, glass mat separators, and improved plate construction. These batteries give 20 watt-hours per pound at the 20-hour rate. Using a GE solid-state control system, the modified Henney Kilowatts have a range of 65 miles compared with 35-40 miles for the original models under comparable conditions.

H. ROWAN CONTROLLERS, INC.

The activities of this Westminster, Maryland, based company in the electric vehicle field are covered in the section on Italian activity in Appendix B.

I. U. S. ARMY ENGINEER RESEARCH AND DEVELOPMENT LABORATORIES

As part of the U. S. Army's continuing development programs on various approaches to electrical propulsion in vehicles (see Section VII), USAERDL has converted an M-37 truck to fuel cell power. The power source was a hydrazine-air fuel cell developed by Monsanto and constructed in 5-kw modules. Four modules were used in the initial conversion to give a 20-kw rating, but the design allows for later use of an 8-module, 40-kw fuel cell.

The curb weight of the converted truck was 6000 pounds, of which 700 pounds was taken up by a conventional dc series motor, 525 pounds by the 20-kw fuel cell system, and 300 pounds by the controller. All of these weights are believed subject to further reduction. The 20-kw power source permitted a maximum speed of 47 mph and steady climbing up a 20% grade. When the 40-kw system is installed, accelerative performance will be fully comparable with trucks having the standard 94-hp gasoline engine.

J. WEST PENN POWER COMPANY

West Penn Power (a unit of Allegheny Power System Inc.) is an electric utility headquartered at Greensburg, Pa. It has constructed a small, open electric car for demonstration purposes. The chassis and suspension were taken from a Volkswagen sedan, and an aluminum body was built onto it. The power source is an assembly of six 12-volt, 205 amp-hour lead-acid batteries, and the motor is a conventional 7.1-hp dc traction motor of the type used in the Henney Kilowatt. The control system designed by West Penn uses thyristors. The overall curb weight is 2160 pounds. With this system a maximum speed of 50 mph has been attained, and under favorable driving conditions the range is as much as 50 miles.

K. WESTINGHOUSE

In 1967 Westinghouse announced the availability of the "Markette," an electric passenger vehicle for highway use, capable of carrying two passengers. The vehicle was derived from the golf carts and personnel carriers which Westinghouse has manufactured since its acquisition in 1964 of Electric Marketeer of Redlands, California. It was intended as an auxiliary vehicle for special uses where its quietness, economy, and smooth performance would offset its limited speed and acceleration. With a curb weight of 1730 pounds, the Markette carried 792 pounds of lead-acid batteries (twelve 6-volt, 217 amp-hour), and its two 4.5-hp dc series motors provided a top speed of 25 mph in 12 seconds from a standing start. The range at one stop per mile was about 50 miles. The vehicle was designed from existing state of the art components and was priced at "under $2000." Optimal solid-state controls to give it greater operating economy would cost about another $500.

The Markette has recently been temporarily withdrawn from production because it does not comply with all of the new federal safety requirements. This points up a significant difficulty for developers of electric vehicles, since changes in specifications can be very costly for vehicles made in small quantities.

L. YARDNEY ELECTRIC

The Yardney Electric Company is operating a Henney Kilowatt in which silver-zinc batteries have been substituted for lead-acid. The higher energy density and power density of the silver batteries give much improved performance. In the original conversion four batteries were used, each having fourteen 85 amp-hour cells. Their total weight was 240 pounds in contrast to the 700 pounds of lead-acid batteries which they replaced. Maximum speed was 55 mph, acceleration 0-30 mph in 5 seconds, and a steady-speed range of 80 miles. Yardney is now planning to reconvert the vehicle for use with batteries of the same type but improved design (the original were intended for service in military aircraft), with which it hopes to improve performance still further.

M. ACTIVITIES OF INDIVIDUALS

Besides these activities of industry and government there are also instances of conversion of conventionally powered vehicles to electric drive by individuals. Among these are the conversion of an MG roadster by Mr. William Roden of San Diego, California, and of a Karmann Ghia by Dr. Hugo Myers of Los Angeles. Mr. John Hoke of Washington, D. C. has constructed his own electric car based on a conventional small car chassis. All three of these vehicles are in regular use.

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APPENDIX B

NOTES ON FOREIGN ACTIVITY

While interest in electric vehicles is less widespread in Europe and Japan than in the United States, many countries, particularly the United Kingdom, are quite active in vehicle design, control development, and investigation of new types of electrochemical power sources. The motivation of this interest is generally concern about air pollution, although the use of small electric vehicles to relieve traffic congestion and parking problems in the cities is equally important. In Europe, petroleum-based fuels are taxed more heavily than in the United States, and, as a result, there is proportionately greater incentive to use electric vehicles. In the materials handling field, for example, well over half of European lift trucks are electric. Electric propulsion is thus at a higher level of acceptance than in the United States.

The following are some notes on the more prominent of the foreign activities.

A. UNITED KINGDOM

Activity in electric highway vehicle development in the United Kingdom takes place at two levels. The first involves the manufacture of electric trucks for specialized purposes, primarily milk delivery, and is a well-established commercial undertaking. The second concerns the development of a small car, generally a two seater for use as a commuter vehicle in urban areas. In addition, some research is being done on novel types of electrochemical power sources.

The use of electric trucks on United Kingdom highways has increased substantially over the last 15 years; by the end of 1967 there were approximately 45,000 in service. About 85% of them are for domestic milk delivery. The most prominent manufacturers are Austin Crompton Parkinson (ACPEV), Smith's Delivery Vehicles, Stanley Engineering, and W & E Vehicles. A typical truck having a carrying capacity of about 3000 pounds is shown in Figure B-1. Power sources for these vehicles are typically 72-volt, 300 amp-hr lead-acid batteries, which give a range of 20-30 miles with 200 stops and a maximum speed of about 15 mph. Their robustness, ease of maintenance, and low-operating costs make them very popular with dairies and others engaged in door-to-door delivery.

Hybrid electric trucks have recently appeared in the United Kingdom. Some new models being offered by Austin Crompton Parkinson achieve extended range through use of a small propane-fed engine generator.

Electric car development, which is still at the prototype stage, has focused on small vehicles, usually two seaters, to be powered by lead-acid batteries and to be priced at around $800. A photograph of the "Scamp", a typical vehicle of this type, is shown in Figure B-2. These vehicles generally have a maximum speed of about 40 mph and a range of 30-40 miles

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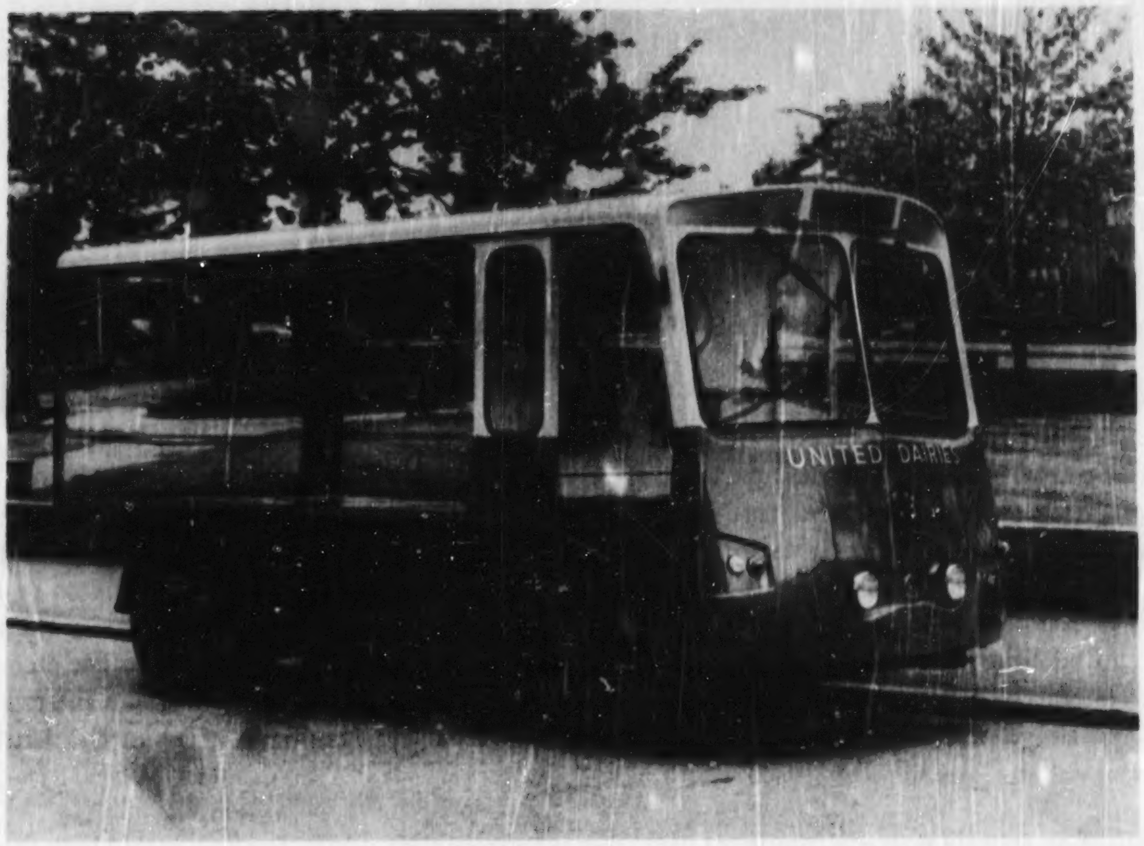
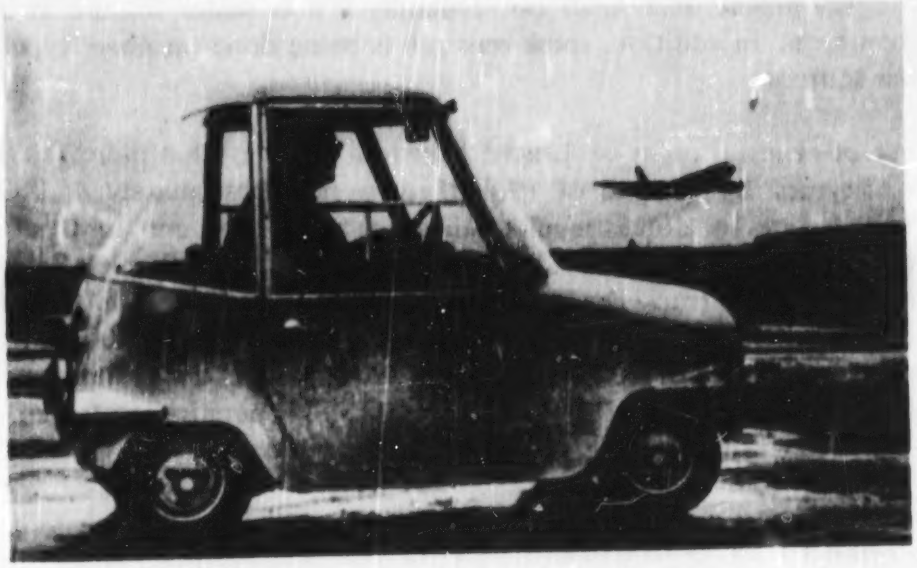


Courtesy of W&E Vehicles

FIGURE B–1 BRITISH ELECTRICALLY DRIVEN MILK TRUCK



Courtesy of Scottish Aviation, Ltd.

FIGURE B–2 THE SCAMP: A DEVELOPMENTAL VEHICLE under non-stop driving conditions. Table B-1 lists specifications for some of them. The two Electricity Council Minis and the Peel Trident are conversions from conventionally powered cars, but the Scamp (of which a dozen were built) and the Ford Comuta were designed as electrics. All are two-seaters except the Trident, which is essentially a single-seater.

Besides the cars listed in Table B-1, design, mock-up, and prototype construction is being undertaken by Tube Investments, Hamblinetta (Flamenco), Carter Engineering (Carter Coaster), and Telearchics Ltd. (Winn City Car). These cars are being designed to have lightweight plastic bodies.

Most research on power sources has concentrated on fuel cells. Shell Oil Company carries out its research in England and has successfully demonstrated a 5-kw fuel cell system operating on reformed methanol with air as the oxidant. Chloride Electrical Storage, the largest British battery manufacturer, has shown a 2-kw hydrogen-oxygen cell fed by cylinder gas; it is used to power an in-plant tractor truck. Energy Conversion Ltd. is also active in fuel cell research.

In the battery field there is considerable interest in improved lead-acid batteries with thinner plates and higher energy and power density. This work is being carried out by battery companies such as Chloride and Oldham and at the laboratories of the Electricity Council. In the metal-air battery field, Joseph Lucas Ltd. and Crompton-Parkinson (Division of Hawker Siddeley) have cooperative programs with General Atomic and Leesona, respectively. British Motors has recently announced its interest in developing a vehicle to be powered by a zinc-air battery of the Leesona type in its subsidiary ACPEV, jointly owned with Crompton-Parkinson. No comment was, however, made on the prospective economic feasibility of such a vehicle.

Work on solid-state control systems is going on at Lansing Bagnall, Ltd. and at ACPEV. The initial application for this development is, of course, in the electric truck-materials handling area. Programs aimed at improving the characteristics of motors are being carried out at Bristol University and the laboratories of the Electricity Council at Capenhurst.

B. FRANCE

The major French activity in electric vehicles is a government-coordinated program directed toward the development of a fuel-cell-powered car by 1971. Present plans call for the power source to be a hydrogen-oxygen fuel cell with a rated power of 25 kw.

Various aspects of this development program are being conducted by specialized contractors. The government-controlled automobile company, Renault, will build the vehicle, and companies such as CSF and C. F. Thomson-Houston are developing motors and control systems.

TABLE B-1

SPECIFICATIONS OF SOME BRITISH EXPERIMENTAL ELECTRIC VEHICLES

	Curb Weight (lb)	Motor hp (Continuous Rating)	Controls	Batteries	Acceleration	Maximum Speed (mph)	Range (miles)
Electricity Council AEI Mini-1	2,499	12 hp	Thyristor	96 v, 66 amp-hr (1-hr rate) 829 lb	0-30 in 12 seconds	41	30 non-stop at 37 mph
Electricity Council Telearchics Mini-2	2,378	2 at 3 hp	Carbon pile	64 v, 110 amp-hr (1-hr rate) 823 lb	0-20 in 5 seconds	40	28 non-stop at 40 mph
Peel Engineering Trident	600	24 volt 5 hp	Carbon pile	24 v, 153 amp-hr	0-30 in 7 seconds	35	
Scottish Aviation Scamp	1,000	2 at 2.7 hp	Carbon pile	48 v, 105 amp-hr (5-hr rate) 400 lb	0-30 in 10.5 seconds	35	30 non-stop
Ford Comuta	1,200	2 24 volt 5 hp	Thyristor	48 v, 85 amp-hr (1-hr rate)	0-30 in 14 seconds	> 30	40 at 25 mph

A major fuel cell program is under way at the Institut Française du Petrole supported by development work on carbon-based electrodes at Société le Carbone Lorraine and on sintered-metal-based electrodes at Ugine-Carbone. Other types of fuel cells are also under investigation: there are programs on a Bacon-type fuel cell at ONIA (Office National Industrial d'Azote) and on hydrazine fuel cells at Alsthom. This latter company has recently announced a joint vehicle development program with the automobile manufacturer, Peugeot. Metal-air batteries are under investigation at CIPEL.

An interesting example of electric vehicle application in France is the use of a battery-powered bus between the airport and the city of Marseilles. This is a full-size vehicle weighing 36,000 pounds and capable of carrying 26 people seated plus 54 standing. It is powered by a 96-volt, 750 amp-hour lead-acid battery that provides a range of 50 kilometers.

C. GERMANY

A small but significant number of electric delivery trucks were in use on German highways prior to 1950; the system of license fees was then changed so that the fees were based largely on weight, and this virtually eliminated the vehicles. In recent years there has been a revival of interest, although on a much smaller scale than in the United States and the United Kingdom. However, self-propelled rail cars powered by lead-acid batteries are in substantial use on the German national railroads. They were introduced after World War II, and about 300 are now in service.

Most of the work in Germany on novel power sources has been focused upon fuel cells. Both Siemens-Schuckertwerke and Varta have large groups working on hydrogen-oxygen fuel cell development, and Bosch has sponsored work on methanol fuel cells at the Battelle Institute in Frankfurt. The group at Varta has an interesting concept for regenerative braking. The energy from the generator is used to electrolyze water, providing hydrogen and oxygen which are stored and used subsequently in the fuel cell.

D. ITALY

Italian participation in electric car development is confined to the design and construction of small experimental vehicles with relatively conventional motor and control systems, powered by lead-acid batteries. One of the more prominent of these vehicles, shown in Figure B-3, was built by Ghia S.p.A. and De Tomaso Automobili, subsidiaries of the Rowan Controller Company of Westminster, Maryland. This four/five seat vehicle has a curb weight of 1,300 pounds and is powered by lead-acid golf cart type batteries. The maximum speed is 40 mph and the range 50-100 miles, depending on driving conditions. A relatively inexpensive solid-state controller is used which operates by switching the field current of the two 8-kw dc compound motors specially designed for this application by the General Electric Company. The controller circuit is also utilized for regenerative braking.

A very small electric vehicle called the "Urbanina" of unconventional design and for use in congested downtown locations has also been exhibited. This car weighs only 800 pounds. The passenger compartment holds two people and is in the form of a rotating turret. A range of 50 miles and top speed of 38 mph have been reported. Other Italian electric cars involve conversions of conventional Fiat 500's.

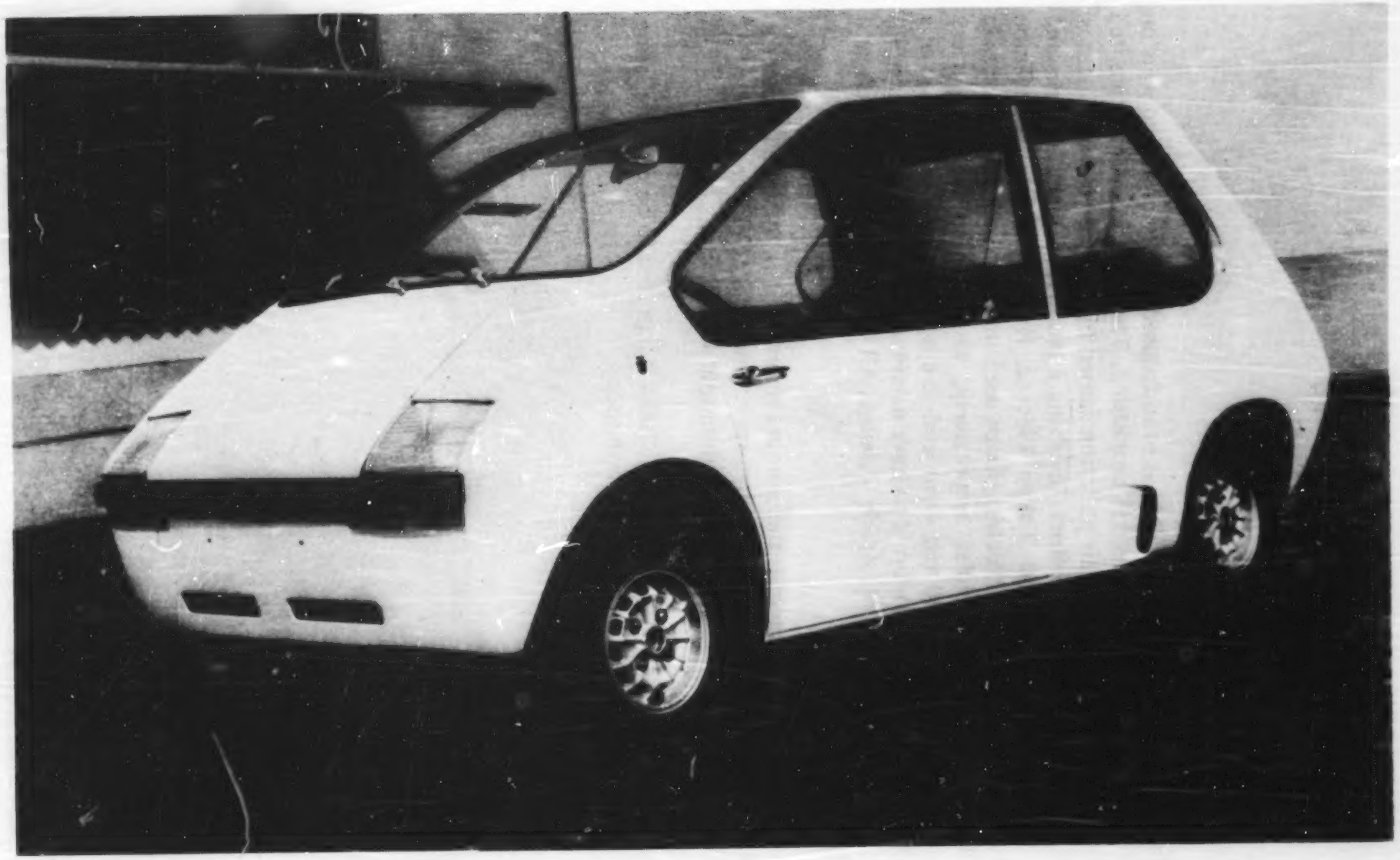
E. SWEDEN

Urban concentration in Sweden is much less than in other developed countries, and the comparatively large distances between populated centers make electric vehicles less immediately attractive; nevertheless, interest in their development is strong. The most notable Swedish activity is in fuel cell development: ASEA has constructed the world's largest fuel cell system, which uses cracked ammonia and has a power rating of 240 kw. The immediate application was as a power source for submarines, but smaller modules of the system have been used to power experimental lift trucks, and electric highway vehicles are also under consideration.

In a recent demonstration co-sponsored by the local Stockholm electrical utility, ASEA exhibited an electrically powered SAAB. This vehicle contained a 120-volt nickel-cadmium battery weighing 1,000 pounds. It had a range of 25 miles, falling to about 15 miles in city traffic. The top speed was 43 mph.

F. BELGIUM

The most significant work on electric vehicles in Belgium is being carried out by Ateliers de Constructions Electriques Charleroi (ACEC), which has developed a full sized diesel-electric bus. This vehicle has twin electric motors built into its back wheels. While built largely for experimental purposes, the bus spends most of its time in local service in the town of Charleroi. In the present model no auxiliary traction battery is used; electricity is supplied by the diesel-powered generators as needed.



Courtesy of Rowan Controller Corporation.

FIGURE B–3 PROTOTYPE ELECTRIC CAR BUILT IN ITALY BY SUBSIDIARIES OF ROWAN CONTROLLER CORPORATION

G. JAPAN

Japanese development of electric vehicles has been focused mainly on the conversion of small, conventionally powered cars to electric propulsion. The work has been prompted by the country's increasing concern about air pollution caused by heavy traffic in the cities. Three of these program are collaborative efforts involving a number of manufacturers and are organized by three utility companies: Tokyo Electric, Kansai Electric, and Chubu Electric. The Kansai Electric and Tokyo Electric groups used standard lead-acid batteries in conversions of 800 cc and 360 cc vehicles, respectively, while Chubu Electric Battery Company developed a special 80-volt, 400 amp-hour lead-acid battery for its conversion of a 1, 500-cc vehicle. All these vehicles are reported to have maximum speeds of the order of 40 mph and a range of about 50 miles at steady driving. All have thyristor controls and regenerative braking.

An interesting recent development is the announcement by Tokyo Shibaura Electric Company (Toshiba) of a small car powered by a high-speed brushless dc motor. Rated at 27 hp at 20,000 rpm, the motor gave the vehicle a maximum speed of 62 mph.

In addition to the above activity, the city of Osaka is reported to be contemplating purchase of a fleet of small electric buses for downtown use.